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DSRC
DEFENSE SCIENCES
RESEARCH COUNCIL

SUMMARY REPORT

DEFENSE SCIENCES RESEARCH COUNCIL SUMMER CONFERENCE

La Jolla, California
July 1996

Sponsored by
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Final Report compiled by
Charles Evans & Associates

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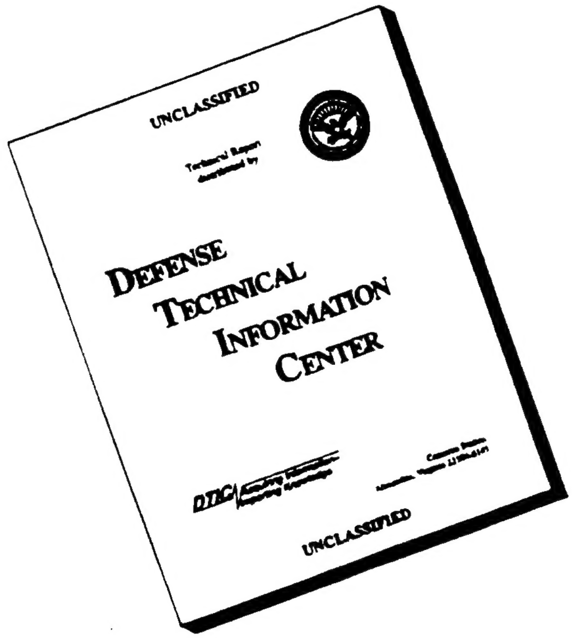

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SUMMARY REPORT OF THE DEFENSE SCIENCES RESEARCH COUNCIL SUMMER CONFERENCE

La Jolla, California
July 1996

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INTRODUCTION

This report is a summary of the 1996 DARPA-Defense Sciences Research Council Summer Conference held from July 8, through July 31, 1996, in La Jolla, California. The report is submitted to DARPA soon after the conference to allow timely utilization of the results from the conference workshops.

During the year, workshops and program reviews are attended by smaller groups of Council members. These reports are made directly to DARPA and are included in the report submitted at the end of the contract year.

The principal task of the ONR-DARPA Contract is to bring together a group of the country's leading scientists and engineers for an extended period, to permit them to apply their combined talents in studying and reviewing future research areas in defense sciences for the Department of Defense.

The technical direction of the Council is by a Steering Committee comprised of seven representative members of the Council who work with DARPA management to select the relevant topics for the annual Summer Conference, and with the Council membership to develop new areas in defense research. The Council also serves as a resource for other DARPA offices.

The membership of the Steering Committee and the Council varies from year to year in response to the research areas of major interest to the Department of Defense. The 1996 Steering Committee membership is given on the following page and the 1996 Council membership is given on pages v–vi. The DARPA and ONR participants in the 1996 DSRC program are given on pages vii–viii.

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July 1996

DSRC SUMMER CONFERENCE SCHEDULE

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
1	2	3	4 Holiday	5
8 *Detection of Unexploded Ordnance* D. Evans	9 *Solid State Mechanical Actuation* Cross/T. Evans	10 New *Bio Materials & Interfaces* Whitesides	11 *Nanomaterials* Heuer/Ehrenreich	12 *Advanced Technologies for Defense Against Biological Warfare Agents* Whitesides
15 *Energy from the Environment* Whitesides	16 DARPA Day Beasley	17 *Mesoscopic Machines* Kovacs	18 New *Materials for MEMS* Cross/Kovacs/Heuer	19 *Interfaces: Physics & Chemistry for Optical & Electronic Materials* Osgood
22 *Advanced Device Physics Concepts* Ferry/Beasley/McGill	23 *Advanced Lithography* Fuller/McGill	24 *Massive Memory* McGill	25 New *Materials for Active Optical Circuits* Osgood	26 *Future of Optics in Defense Systems* Miller
29 *Writing Day 1*	30 *Writing Day 2*	31 *Wrap-Up Day Presentations* Beasley		

The agenda for the Summer Conference is prepared initially during the prior year's conference with input from ARPA and the Council. This is refined at subsequent Steering Committee meetings and the workshops are organized. The calendar for the 1996 Summer Conference is shown in the figure above.

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DETECTION OF UNEXPLODED ORDNANCE (UXO)

C. Evans, R. Lytikainen, R. Rapp (DSRC)
R. Dugan (DARPA)

EXECUTIVE SUMMARY

Objective

Examine state-of-art and promising novel techniques, especially chemical, for the detection of unexploded land-based ordnance, in particular antipersonnel mines.

Relevance to DoD

The United Nations estimates that 110 million mines have been laid in 62 countries as the result of civil and international conflicts. Per year, 26,000 noncombatants are maimed or killed by UXO accidents, about 20% children. The number of land mines deployed in the world is constantly increasing, at a rate that greatly exceeds those cleared. From the recent military actions in Viet Nam, Iraq, and Bosnia-Herzegovina, land mines pose a continuing threat to allied military and native civilian personnel. Civil strife and terrorist actions have led to a more random deployment of land mines threatening civilians around the world, so the detection and destruction of UXO also represent a necessary humanitarian quest.

Summary of Scientific and Technical Issues

The current state of land mine detection and removal technology is inadequate for any of the three regimes of operational interest: fast removal during combat during all weather conditions, slower clearance operations in fair to all weather conditions outside direct fire, or peacetime operations in fair weather. Currently, available traditional physical techniques (metal detectors) provide detection of some mines or even most UXO, but suffer from many false positive signals, depending on the method, the soil conditions, and the amount and nature of ubiquitous metallic and other ground clutter. Despite continuing significant development funding, these physical techniques have not yet achieved an acceptable effectiveness nor adequate configurations with regard to size, weight, power requirements, logistics, or minimal training for battlefield deployment.

In contrast, one controlled study of mine detection by canines showed that their olfaction capabilities permit the highest positive detection capability (>95%), and a low false alarm response (<2%). Except for metal detectors for metal containing UXO and hand-held probes, dogs are the only detection system used in the field. The success of dogs in mine detection suggests that chemical methods (electronic analogs of dog noses) should show promise to achieve similar or improved detection efficiency, without the liabilities inherent to the use of dogs.

To ascertain whether other groups experienced in UXO and explosives detection were using methods adaptable to land mine detection, summarizing presentations were made by: George Pollitt (Navy Mine Warfare Command), James Petrousky (Office of Special Technologies, "K-9 Corps"), and Susan Hallowell (FAA). Except perhaps for anti-invasion mines in the shallow surf zone, the Navy direct detection experience and removal methods are not transferable to land mine detection. Interestingly, Navy-trained mammals using their sonar capabilities are by far the most effective detector of submerged mines. At airports, the FAA uses nuclear, X-radiographic, and eddy current methods to detect metal weapons. Because canines are again the most effective in

detecting/smelling explosives, narcotics, toxics and agricultural products, the FAA is investigating new chemical methods, e.g. a small ion mobility spectrometer, for the chemical sampling of vapors, particles and adsorbents from passenger's hands, clothing, and baggage. However, the dimensions, weight, and power requirements for an airport detection system are far less stringent than those for land mine detection in the field.

The existing physical methods for detection of UXO, and more specifically plastic (very low metal content) land mines, differ greatly in what they detect, in their advantages and in their liabilities. Frank Paynter (Ohio State Univ.) explained that Ground Penetrating Radar (GPR) detects differences in the subsurface propagation of the radar signal, and different targets can provide different identifiable signatures. The target need not be magnetic or even metallic, but surface and subsurface clutter (e.g. rocks), noise and RF interference affect the response and lead to many false alarms and some missed positives. The effectiveness in detecting certain targets depends upon the frequency chosen, and the dielectric constant and electrical conductivity of the particular state of a given soil. The technique is optimized for sandy soil, and worst for wet packed soil. A portable GPR detection unit is available, but its efficiency would be enhanced by modeling of the ground clutter, soil conditions and target response. Even with some further optimization, GPR offers promise for only limited applications.

Magnetometers detect the perturbation in the local geomagnetic field caused by a ferromagnetic object. As explained by Thomas Altshuler (IDA), magnetometers (MAG) can detect large UXO at depths exceeding 4 meters, but they have difficulty recognizing targets in a soil highly cluttered by scrap steel. A variety of magnetometers are available (vector field, full field, gradiometer), some as hand-held models. While the magnetometer would not be useful in detecting plastic land mines, effective use of this technique to detect ferrous objects also requires improved modeling of the clutter and UXO signatures, i.e. improved signal processing and UXO recognition.

David White (Johns Hopkins Univ.) summarized the nature and status of Magnetic Induction (MI) methods in mine detection. The technique senses the reradiated magnetic field from the eddy current induced into a metallic object by a magnetic field from a source transmitter. The effective penetration depth depends upon the chosen frequency, and MI is most effective for detection in media of low electrical conductivity, such as frozen or dry soil. So MI can detect metallic targets, and even the metal firing pins of some plastic mines. Holographic imaging, developed at JHU/APL, uses Fourier transforms for signal interpretation and assistance in target resolution and recognition. MI is the most effective physical system in current use.

As discussed by Edward Winter (Technical Res Assoc.), Infrared (IR) techniques are intended to detect temperature anomalies at locations of buried objects, disturbed soil, etc., and some single wave band sensors can detect a temperature difference as small as 0.1 degree. The IR technique is frequently tied to daytime aerial inspections, and nighttime detection is confused by clutter and vegetation. The DARPA-developed multi/hyperspectral sensor can detect disturbed soil in a cluttered environment for days to months after burial, but a heavy rain will defeat that capability. The technique seems to be dependent upon expert interpretation of IR surveys, and seems to offer little promise as a prime reliance detector.

Anne Andrews (IDA) described the effectiveness of physical (GPR, MAG, MI and IR) detection devices in a competitive test program at Jefferson Proving Grounds (JPG) in 1994. Overall, 20 ground-based and 6 airborne platforms were tested and evaluated according to criteria considering location accuracy, false alarms, lucky matches, etc. The overall disappointing performances included: 1. no airborne or radar platforms detected anything, 2. highest probability of detection was <70%, 3. all techniques detected more false alarms than correct signals, 4. no technique could

find 20 plastic antipersonnel mines, and 5. no method could discriminate ordnance from intentional clutter, or one type of ordnance from another. The specific ranking of one technique compared to another was probably influenced by the very wet soil condition. A JPG phase II competition in 1995 has not been fully interpreted, but the 15 competitors provided an increase in the total detections, and an increase in false alarms. Another detection demonstration was held at A. P. Hill, with GPR, MI, and IR represented. The ranking of the systems was changed according to different soil and weather conditions. While metal-cased mines were generally reliably detected, low-metallic mines were detected by a limited number of methods (especially by MI. L nonmetallic mines were detected by systems using GPR, but small nonmetallic mines were largely undetected.

A series of six presentations was aimed at exploring methods differing from the traditional methods already discussed. With recognition of the effectiveness of canines in detecting UXO, John Kauer (Tufts) discussed the nature of the distributed specificity of the olfaction process in dogs, and the path of the resulting signals to the brain. Recognition of odors may be associated with provision of many different molecular vapors to activate a given receptor, and the simultaneous stimulation of numerous such specific sensoring cells. Adsorbents on particles can also provide the necessary molecules for adsorption and detection. Mimicking such olfaction for artificial biosensors will require arrays and ensembles of sensing elements, with molecular transducers providing signals to fast biomolecular receptors to achieve recognition by the brain. Harold Bright (ONR) elaborated more quantitatively on the olfaction process and pointed out how cross-reactivity within a detector array leads to robust selectivity, reversible time response, good dynamic range, and fewer false positives without the need for reagents. Protein biomolecular receptors for metal ions and organics rely on combinational libraries that contain billions of sequence variants. Nanotubes from peptides offer very specific geometric sites for molecular adsorption. Current molecular design menus call for the randomizing of single unfolded n-mers, and then folding these molecules to form a shape space library which can be encoded. A future biosensor may consist of a sensor head coated with many ($>10^6$) receptors, each with a transduction (e.g. fluorescence or luminescence) apparatus which responds in color and intensity. The resulting pattern would be transmitted by an optical fiber bundle with resolution of 10^6 pixels/cm^2, and pattern recognition would be achieved by a trainable neural net processor. Signal processing and an optimized array architecture would lead to expansion of the sensitivity and dynamic response ranges.

Alan Garroway (NRL) described the "nuclear" methods for land mine detection: thermal neutron analysis (TNA), X-ray backscatter, NMR, nuclear quadrapole resonance (NQR), etc. Generally, TNA lacks the needed specificity for detection of high-nitrogen-containing compounds, e.g. TNT, it provides a weak signal, suffers from cosmic noise, and requires large, expensive and sophisticated equipment. X-ray (Compton) backscatter imaging depends upon the atomic mass of the elements, so variations in density and composition and multiple scattering along the irradiated path pose problems for imaging. While the use of two detectors can provide improved target localization and remove some clutter signals, the shallow penetration depth of 100 kev gamma rays is still a problem. More promise for the detection of explosives is offered by NQR, which has already found application in airport security applications. The NQR method has high specificity, with no use of a magnet or ionizing radiation, but only a bulk target is detected with no imaging of geometry. While the method offers some promise for development, no inexpensive portable model exists today, and the technique is defeated by RF shielding.

A number of traditional analytical chemistry techniques were discussed by Wayne Bryden (Johns Hopkins Univ.). Specifically for the real time detection of vapor from land mines, the two instruments recommended were the Ion Mobility Spectrometer (IMS) and the Mass Spectrometer. In the IMS, the atmospheric gases are sampled through a pinhole and ionized using a ^{63}Ni source.

From an ion-molecule reaction volume, the ions are accelerated across a field-driven drift region and separated in time at the collector according to their mass. Although the optimum conditions of high temperatures, low humidity, etc. would not be present for field deployment, high sensitivity (ppb-ppt) small (hand-held) models have been manufactured. Although the MS offers high sensitivity, and the time-of-flight model can be small and lightweight, the technique does require a vacuum pumping system, and the equipment can be fragile, power intensive and slow.

Frances Ligler (NRL) described new systems for the detection of explosives in solutions, e.g. gas chromatography (GC) can readily analyze for TNT to 3 ppb in soil. Two new NRL biosensors, whose detection systems utilize a biomolecule or biomimetic to detect the substance of interest, were discussed: a fiber optic system and a flow immunosensor. While each of these systems was effective in detecting TNT, the methodology is inherently slow and requires that the target be dissolved in solution. Adaptation for field detection of UXO is not evident.

Nathan Lewis (Cal. Inst. Techn.) described a conducting polymer application as an electronic nose. A wide range of different polymers exhibit a wide range of hydrophobic behavior, and the adsorption of different organic vapors causes different degrees of swelling for different polymers. If a large number of sensors comprising different polymers are each impregnated by an electronic conducting film, e.g. carbon black, the differing adsorption of a given vapor component by a given polymer results in different degrees of swelling, which are monitored by an increase in the dc resistance between two probes for each sensor. Combinatorial arrays of such polymer sensors provide differing specific responses to a wide range of chemical vapors, including TNT. The further development of this method, with miniaturization, linking to neural networks, etc., may lead to a valuable chemical sensor for vapors of many sorts, including those associated with UXO.

Discussion following the presentations raised interesting unexplored possibilities, such as the identification or development/training of bacteria or insects which can react to vapors of explosives. So swarms of some insects could hover over a mine site or stand watch at the entry point to a military base. The dust and vapors above a potential mine field could be collected by a light and unmanned scanning vehicle; these potential carriers of explosive molecules could be deposited upon an indexing filter tape which would then be subjected to remote analysis, either by canines, or else by a chemical technique which would be suitable. The analyses by canines of collected soil batches outperformed other detection methods in South Africa.

Conclusions and Observations

The loss of lives and limbs to UXO, especially plastic antipersonnel land mines, poses a continuing daily hazard to both troops in the field and to the civilian population for decades following the mine deployment. At this time, the traditional physical methods for mine detection are not adequate. But their effectiveness may be improved by mathematical modeling of their signal processing, with characterization of the background, clutter, and targets. The canine is the most reliable detection system, and efforts are being made, with some preliminary success, to mimic the dog's olfaction system in detecting vapors. Improved detection of UXO, especially plastic antipersonnel mines, should be found in the chemical detection systems, some of which are promising. The ultimate UXO detection system must be compact, all-weather, energy efficient and portable by a soldier in the field.

DETECTION OF UNEXPLODED ORDNANCE (UXO)

R. Dugan, C. Evans, R. Lytikainen, R. Rapp

Objective

Examine state-of-art and promising novel techniques, especially chemical, for the detection of unexploded land-based ordnance, in particular, plastic anti-personnel mines.

DoD Relevance

Proliferation of deployment of land-based mines, especially anti-personnel mines, poses a threat to the lives and limbs of the soldier during conflicts, and to the soldier and civilians for many years following the conflict.

DoD must develop new reliable all-weather systems with minimum size, weight and power requirements, for positive detection and identification of mines, with minimal false alarms.

Scientific & Technical Summary

> **Status of Traditional Physical Detection Methods Navy Mine Warfare (George Pollitt, MWC)**

- Ground Penetrating Radar (Frank Paynter, OSU)
- Magnetometers (Tom Altshuler, IDA)
- Magnetic Induction (Dave White, JHU)
- Infrared Techniques (Ed Winter, Tech. Res. Assoc.)

> **Current Status of Detection Efficiency, Alternative Uses**

- Competitive Field Test Program (Anne Andrews, IDA)
- Use of Canines (Jim Petrousky, Off. Spec. Services)
- Airport Security (Susan Hallowell, FAA)

> **Prospective Improved/Preferred Technology**

- Olfaction Physiology - Key to Canine UXO Detection (John Kauer, Tufts Univ. and Harold Bright, ONR)
- Nuclear Methods (Alan Galloway (NRL)
- Analytical Chemistry Techniques (Wayne Bryden, JHU)
- Chemical Detection in Solutions (Frances Ligner, NRL)
  Conducting Polymer Electronic Nose (Nathan Lewis, CIT)

> **Brainstorming Discussion**

- UXO
- Terrorist threat to bases (later session)

Traditional Physical Methods

Ground Penetrating Radar:

In principal, target need not be metallic, but GPR today misses targets, reports many false alarms, and responds to ground clutter. Possible component of a sensor array. Method needs mathematical modeling of signal response.

Magnetometers:

They detect large, deep ferrous objects, but not plastic mines. Response is confused by ferrous ground clutter. This method also needs improved signal processing and UXO recognition.

Magnetic Induction:

The technique is a metal dectector, sensing the magnetic field from eddy currents induced by a source transmitter. Dependent on soil conditions and presence of buried clutter. Potentially, a component of a multi-sensor array.

Infrared Techniques:

These methods detect small temperature anomolies from buried objects, disturbed soil, etc. Poor success in aerial use for mine detection, and ineffective after rain.

Field Testing Results:

In three broad field testing competitions, all of these techniques missed mines, and reported many false positives. No technique detected plastic land mines. No method from aerial platforms detected anything.

Canines & Olfaction

Canines:

Dogs (any breed with a long nose) are the most effective system for detection of buried UXO. Dogs detect what they are taught to detect; e.g., explosives, drugs, HASMAT, chemical agents, land mines, etc. High sensitivity and few false alarms. But may be subject to chemical masking agents, health problems, short or “bad” work day.

Olfaction Physiology:

Odor recognition is associated with activation of given receptors by specific molecular vapors, and the simultaneous stimulation of numerous such specific sensoring cells. For example, a future biosensor may consist of a sensor head coated with $>10^6$ receptors and a transduction scheme which responds in color and intensity. The resulting pattern would be achieved by an optical fiber bundle with 10^6 pixels/ cm^2, and pattern recognition would be achieved by a trainable neural net processor.

Chemical Techniques

The best current portable technique for specific vapor phase detection of explosive molecules is an Ion Mobility Spectrometer, which samples atmospheric gases. Sensitive bio-based laboratory methods (a fiber optic system and a flow immunosensor) are effective in detecting explosive chemicals in solution, but these are not readily adaptable to the field.

The adsorption of different organic vapors cause different degrees of swelling for different polymers. If different polymers are impregnated by an electronic conducting film, changes in the 2-probe dc electric resistance results from the specific adsorption of various organic vapors. Combinatorial arrays of such polymer sensors provide specific responses to identify unknown vapors. These Cal. Tech. and Tufts University versions of the electronic nose show promise for chemical detection of UXO.

Discussion Ideas

> Develop/teach insects or bacteria, etc., to react to vapors of explosives as in pheranoms.

- Mine/UXO detection
- Portal detection/monitoring

> Analyze adsorption on strewn (magnetic) particles or collect dirt particles for explo sives, not vapor phase.

> Use light, unmanned vehicle to scan potential minefield and collect dust on an indexing filter tape, for remote analysis either by canines or by chemical technique.

Conclusions and Observations

> Loss of lives and limbs to UXO, especially plastic anti-personnel land mines, is a continuing daily hazard to both soldiers and civilians.

> Traditional physical methods for mine detec tion are not adequate, but could be improved by modeling of signal processing.

> The canine is the most reliable UXO detector suggesting utility of bio/chemical methods.

> Developing systems which mimic the dog's olfaction process show promise.

> Ultimate UXO detection array system must be compact, all-weather, energy efficient and portable by a soldier.

Detection of Unexploded Ordnance

Coordinators: C. Evans, R. Rapp, R. Lytikainen and R. Dugan

July 8, 1996 — Day 1

8:30 a.m.	**Introduction** Larry Dubois (DARPA/DSO), and/or Workshop Lead
8:45 a.m.	**Overview of the Sea Mine Problem** George Pollitt (Mine Warfare Command) • Contamination and threat • Detection and neutralization technologies
9:30 a.m.	**Overview of the Land Mine and UXO Problem** Regina Dugan (DARPA/DSO) • Contamination and threat • Current detection technologies used "canonical sensors" • The DARPA approach—explosives detection
10:00 a.m.	**Break**
10:15 a.m.	**Technical Discussions of "Canonical Sensors"**
10:15 a.m	• Ground Penetrating Radar Jonathan Young (Electrosciences Lab)
10:30 a.m.	• Magnetometers Tom Altshuler (IDA)
10:45 a.m.	• Induction Coils David White (APL)
11:00 a.m.	• Infrared Techniques Ed Winters (Technical Research Associates)
11:15 a.m.	**Results from Testing Programs** Vivian George (IDA) • Measuring Performance • Jefferson Proving Ground Results, AP Hill Results, Other
Noon	**Summary**
12:15 p.m.	**Lunch**
1:00 p.m.	**Chemical Detection Technologies** • Vapor Phase Detection
1:00 p.m.	• Olfaction and Mimicking Olfaction John Kauer (Tufts) – Successes and Failures, Current Research Jim Petrousky (OST)

1:45 p.m.	• Other Biologically Inspired Sensors Harold Bright (ONR)
2.30 p.m.	• Array-based Systems Nate Lewis (Caltech) - Surface Acoustic Wave Sensors - Conducting Polymer Sensors - Other
3:15 p.m.	• Antibody Techniques and Determination of the Amount of Explosives in a Minefield Fran Ligler (NRL)
4:00 p.m.	• Condensed Phase Detection Al Garroway (NRL) • Thermal Neutron Activation, X-ray Backscatter, NMR, NQR • Determination of the Amount of Explosive on a Mine Field
4:45 p.m.	**Summary**
5:30 p.m.	**Adjourn**

July 9, 1996 — Day 2

	Chemical Detection Technologies ***(continued from Day 1)***
8:30 a.m.	• Traditional Analytical Chemistry Techniques Wayne Bryden (APL) – Ion Mobility Spectrometers – Mass Spectrometer and GC/MS Systems – Electron Capture Detectors – Photoacoustic Techniques – Emission or Absorption Spectroscopic Techniques – Other
	Other Applications
9:30 a.m.	• The FAA Program in Explosives Detection Susan Hallowell (FAA)
10:00 a.m.	• Terrorism, Counterdrug, Customs, Aviation Security Jim Petrousky (OST)
10:30 a.m.	**Discussion and Brainstorming**
Noon	**Adjourn**

Detection of Unexploded Ordnance – Day 1

July 8, 1996

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July 9, 1996

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SOLID STATE ACTUATORS

E. Cross, A. Evans, A. Heuer (DSRC)
R. Crowe, W. Smith, S. Wax (DARPA)

EXECUTIVE SUMMARY

Workshop Objective

Evaluate the *"authority"* levels achievable with available actuator materials/designs and determine the "authority gap" between these capabilities and the requirements for new military systems. Ascertain the potential for bridging this gap through materials, design and manufacturing innovations.

Relevance to the DoD

Some military applications for solid state actuators have been defined. These include helicopter rotors, aerodynamic wings, vectoring and vibration damping. New opportunities arise for more demanding applications in unmanned aerial vehicles (UAVs), in mesoscopic machines for pumps, heat engines, coolers and in handheld medical imaging instruments. Implementation is impeded by limitations in the actuator *"authority"*, manifest as either work or bandwidth deficiencies. An ensemble of actuator systems that expands the present capability by factors of 2 to 5 would redress these deficiencies.

(i) The greatest potential resides with ferroelectrics (ceramics and polymers) through a combination of novel materials, design and improved manufacturing.

(ii) Electrostatic polymer systems that mimic muscle actuation appear to have unusual promise.

(iii) Hybrids that combine the attributes of each constituent material while minimizing the deficiencies seem interesting: such as electrostatic/electrostrictor ensembles.

The military applications that have yet to be realized because of actuator strain/ bandwidth limitations include several mesoscopic machines, as well as control systems for UAVs and portable medical imaging instruments.

(i) The mesoscopic machines that require improved actuation include pumps, gyroscopes and coolers. The driver is the direct relation between the machine size and the actuator strain. That is, large strain equates to small size.

(ii) The UAV applications are yet to be clearly defined. But, maneuvering and vectoring requirements, as well as efficient propulsion systems, demand compact actuators having high *"authority"*. Detailed needs remain to be specified.

(iii) Handheld ultrasound scanners would have major implications for battlefield medical treatment. The development of such instruments is impeded by the lack of an actuator system with sufficient bandwidth. New concepts in ferroelectric crystals possessing large transformation strain could fill this requirement.

Actuator Systems

(i) Available solid state actuation materials do not individually provide the breadth in *"authority"* required by many military systems. (The relevant *"authority"* measure is the product of force/displacement/bandwidth, fig 1). Examination of the *"authority"* achievable with current materials, within the framework of advanced military systems

achievable with current materials, within the framework of advanced military systems requirements, highlights areas of opportunity for materials that fill the *"authority gap"*. The materials considered included: ferroelcapsectrics, shape memory alloys (SMA), magnetostrictors, electrostatics, biomimetics and hybrids.

(ii) Concurrent assessment of the energy conversion efficiency establishes power requirements.

(iii) Major progress toward implementation of existing actuator materials has been achieved by focusing on reliability, through an integrated activity in materials, manufacturing and design. Evaluation of the reliability tools now available highlighted deficiencies that inhibit successful implementation.

The performance, efficiency and reliability attributed to each actuator material are summarized on figs. 2–5. The factor 2–5 enhancements in "authority" required to enable new military systems seems accessible. The bioinspired muscle and cartilage concepts are new and the attributes/ limitations are more speculative.

Opportunities

Ferroelectrics

Two approaches for enhancing the strain capacity of ferroelectric materials can be combined with ratchet design concepts to provide systems with highly tailorable *"authority"* levels.

(i) Methods that enable the manufacturing of thin multilayer stacks (~1–10 μm per layer) should allow large bias fields without breakdown, thereby enabling large strains (up to 1%), still at high forces (fig. 2). These methods comprise tape casting, followed by HIPing, to process small actuators that can be used in arrays.

(ii) Phase switching materials have inherently higher strain capacity. Materials of this type are limited by hysteresis effects that cause heating and fatigue. New phase compositions that suppress the hysteresis are envisioned, upon using approaches that enhance the reverse switching.

For either material, the strain range can be greatly enhanced by using a ratchet design (fig. 6), albeit with diminished bandwidth. The achievable velocities appear to be 2–20 mms^{-1}. This design provides versatility in the *"authority"* needed to match applications.

Shape Memory Alloys

Shape memory alloys with improved microstructures that have enhanced fatigue resistance have been developed (fig. 3). These alloys extend the applications scope for SMA : especially as hybrids with broader bandwidth materials.

Bioinspired Materials

The electrostatic actuator (fig. 4) made by Higuchi, designated the Dual Excitation Multiphase Electrostatic Drive (DEMED), has been inspired by the operation of muscles. It is a linear motor made from polyimide that uses 3-phase alternating fields to provide displacements with minimal friction. It is capable of large strains at moderate stress levels. The force capacity is limited by breakdown of the dielectric fluid and by buckling of the polymer layers. The approach appears to have potential for appreciable enhancement in the force capacity.

(i) Increase the permittivity of the dielectric fluid by using glycol, acetamide etc.

(ii) Enhance the polymer buckling resistance by using fiber reinforcement.

Moreover, combinations of DEMEDs with ferroelectrics appear to offer interesting opportunities.

Cartilage is a triphasic nanoscale material with two solid phases (collagen fibers and dendritic proteoglycans) and a liquid (Na^+) electrolyte (fig. 5). The displacements achieved through fluid flows in response to a potential are limited to relatively low frequency. But, the strain capacity is large and the achievable forces are appreciable. Synthetic materials that use the same concepts could have durability benefits for low frequency applications, such as wing conformation and maneuvering controls in UAVs, etc.

Summary

1. Because of the limited strain capacity of available actuator materials, many important DoD applications are either suboptimal or not feasible. Improvements in strain capacity without loss of force or speed would broaden DoD application dramatically.

2. There are unexplored opportunities for materials and designs that deliver large strains, while simultaneously achieving large force, broad bandwidth and high energy conversion efficiency. These include phase change materials, new single crystals, ferroelectric ratchets, synthetic muscle or cartilage and novel hybrids.

3. Since it has not yet been possible to optimize all parameters in a single material system, there is an urgent need for a process that matches the new materials/design concepts to DoD applications, with concurrent reliability, manufacturability and efficiency goals.

Implications

1. Put in place a procedure for matching the actuator "authority" requirements for military systems with materials/design innovations.

2. Promote the development of high authority actuator ensembles.

3. Combine the attributes of two or more materials into versatile hybrid designs.

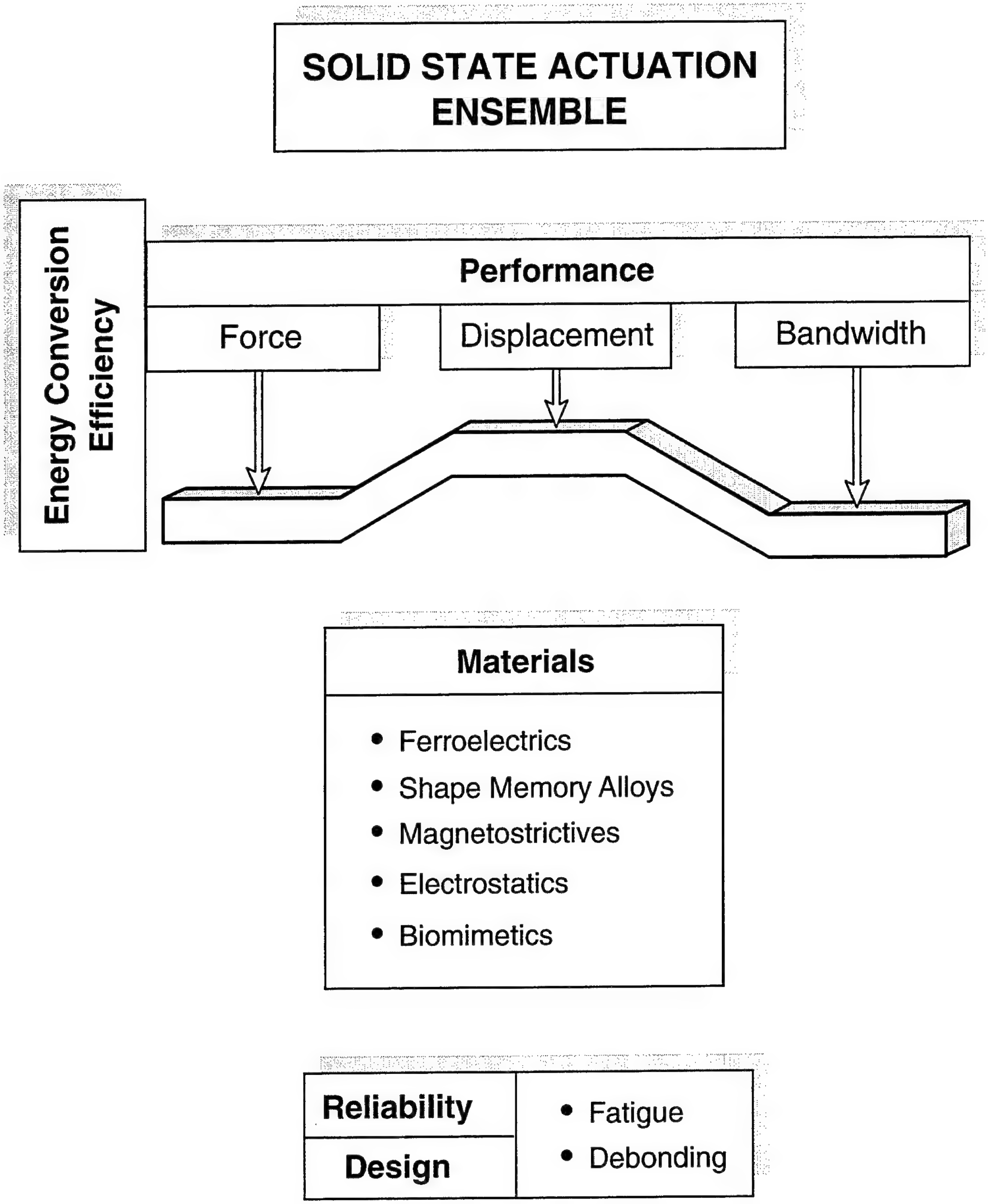
HIGH STRAIN SOLID STATE ACTUATORS

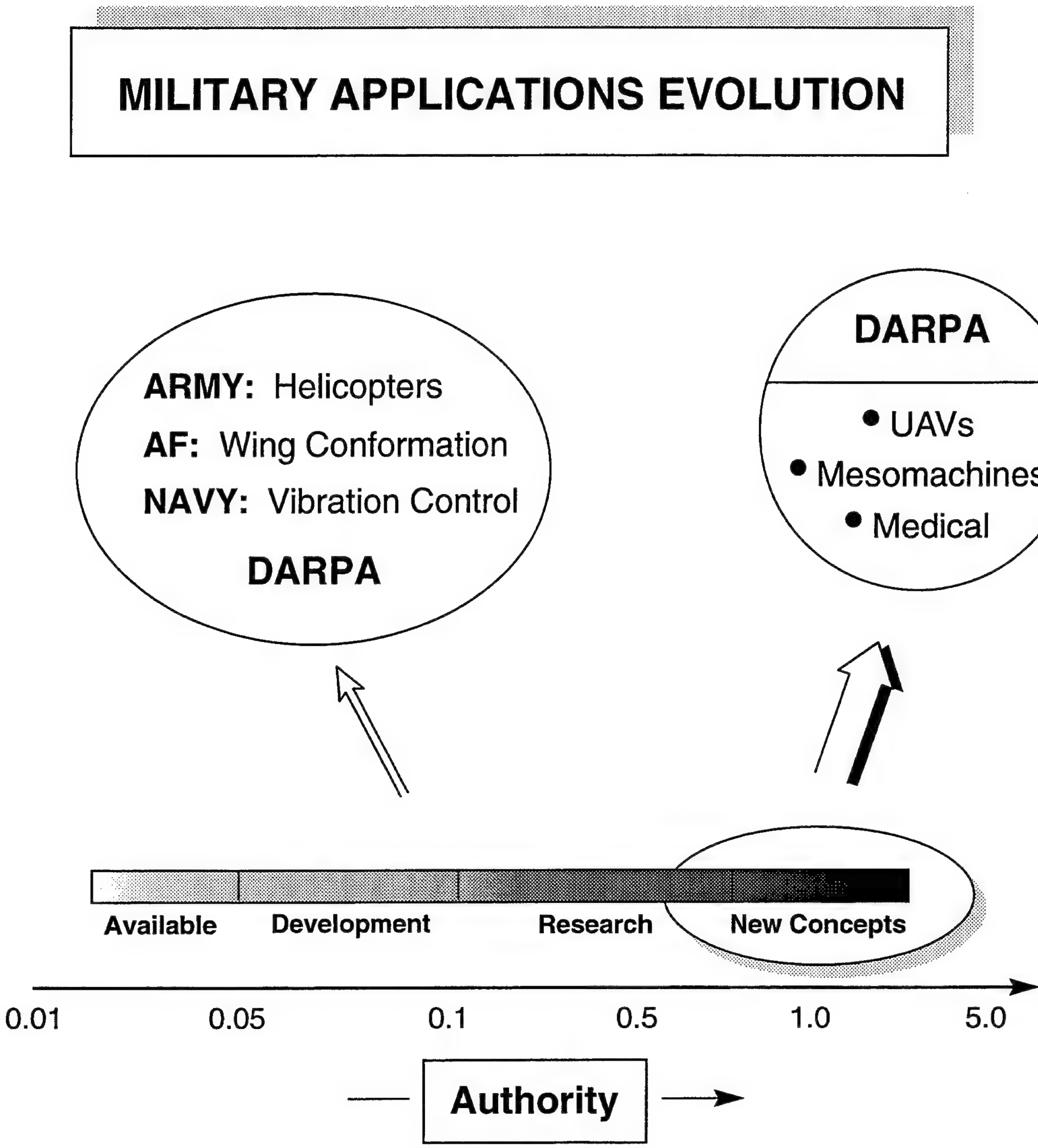
E. Cross, R. Crowe, A. Evans,
J. Hutchinson, A. Heuer, W. Smith, S. Wax

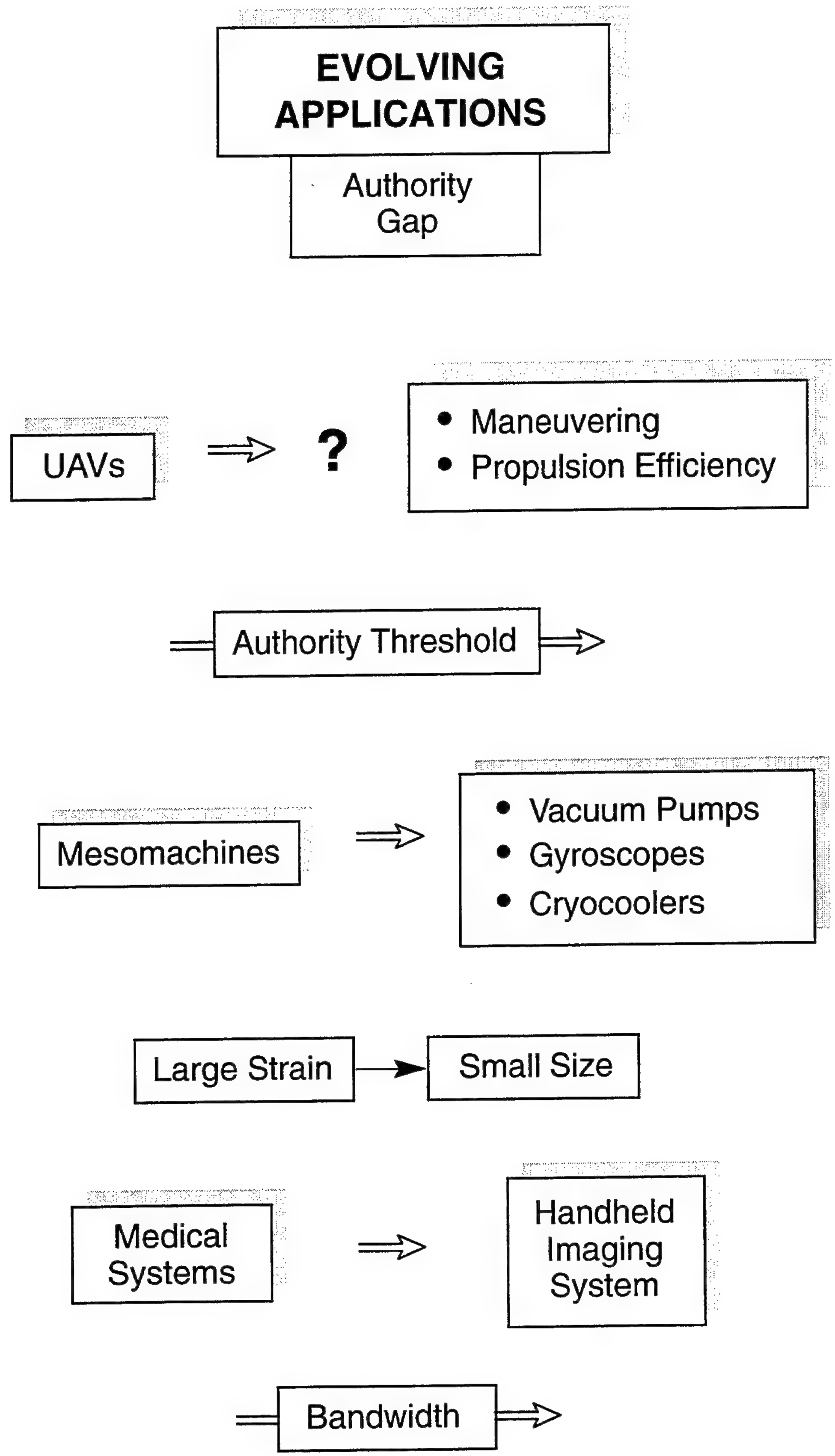
Objective

The "Authority Gap"

- DoD Applications Requirements
- High Strain Actuators
- Materials Opportunities


SOLID STATE ACTUATION ENSEMBLE
Energy Conversion Efficiency
Performance
Force
Displacement
Bandwidth
Materials
• Ferroelectrics
• Shape Memory Alloys
• Magnetostrictives
• Electrostatics
• Biomimetics
Reliability
Design
• Fatigue
• Debonding


MILITARY APPLICATIONS EVOLUTION
ARMY: Helicopters
AF: Wing Conformation
NAVY: Vibration Control
DARPA
DARPA
• UAVs
• Mesomachines
• Medical
Available
Development
Research
New Concepts
0.01
0.05
0.1
0.5
1.0
5.0
Authority


EVOLVING APPLICATIONS
Authority Gap
UAVs
?
• Maneuvering
• Propulsion Efficiency
Authority Threshold
Mesomachines
• Vacuum Pumps
• Gyroscopes
• Cryocoolers
Large Strain
Small Size
Medical Systems
Handheld Imaging System
Bandwidth

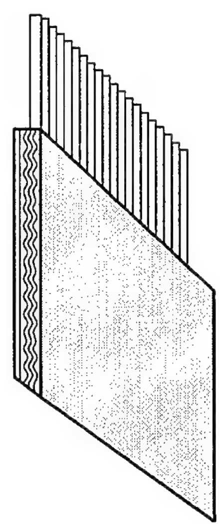
SHAPE MEMORY MATERIALS

NiTi

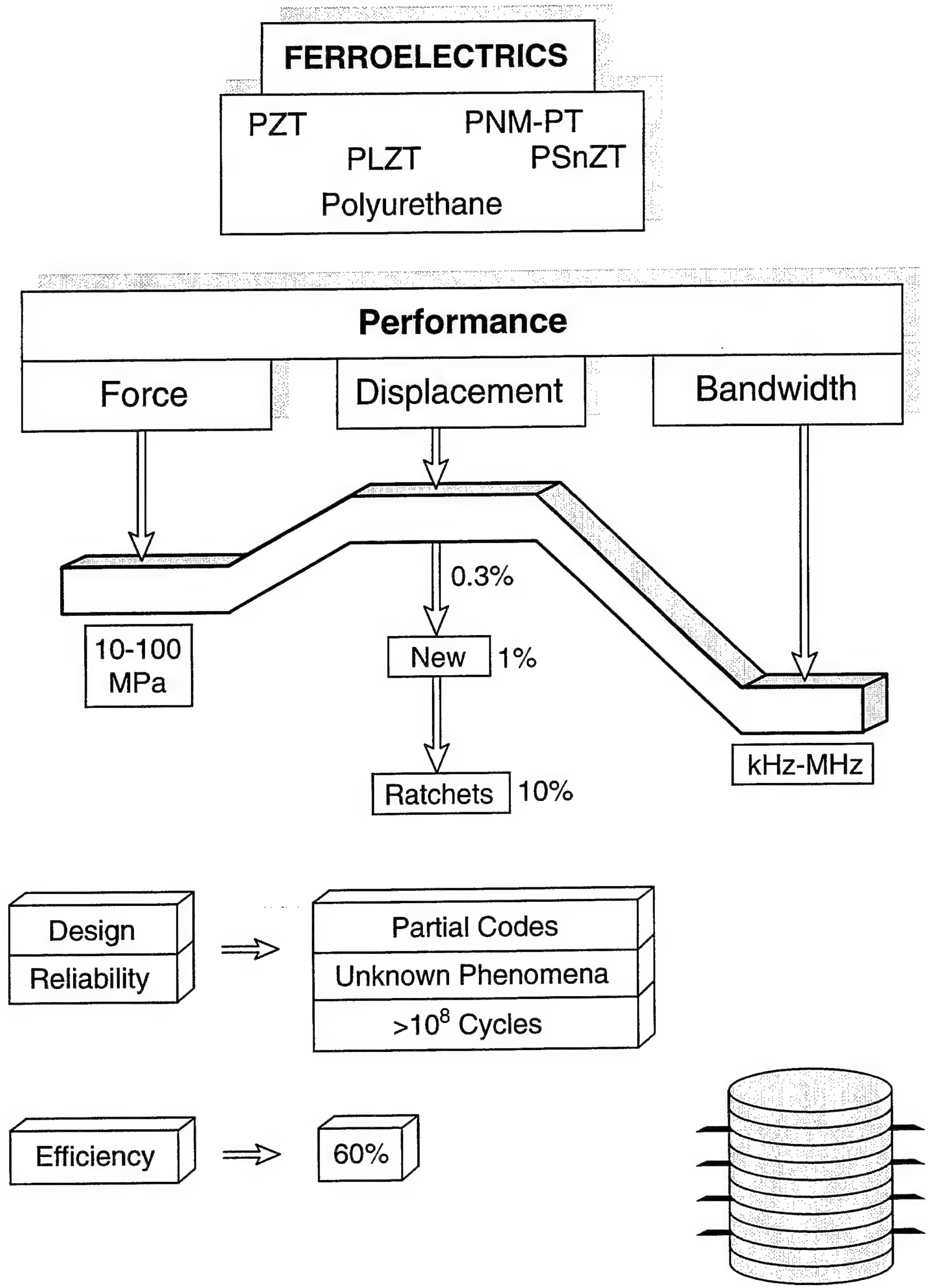
Performance

Force	Displacement	Bandwidth
400 MPa	5%	<0.1Hz

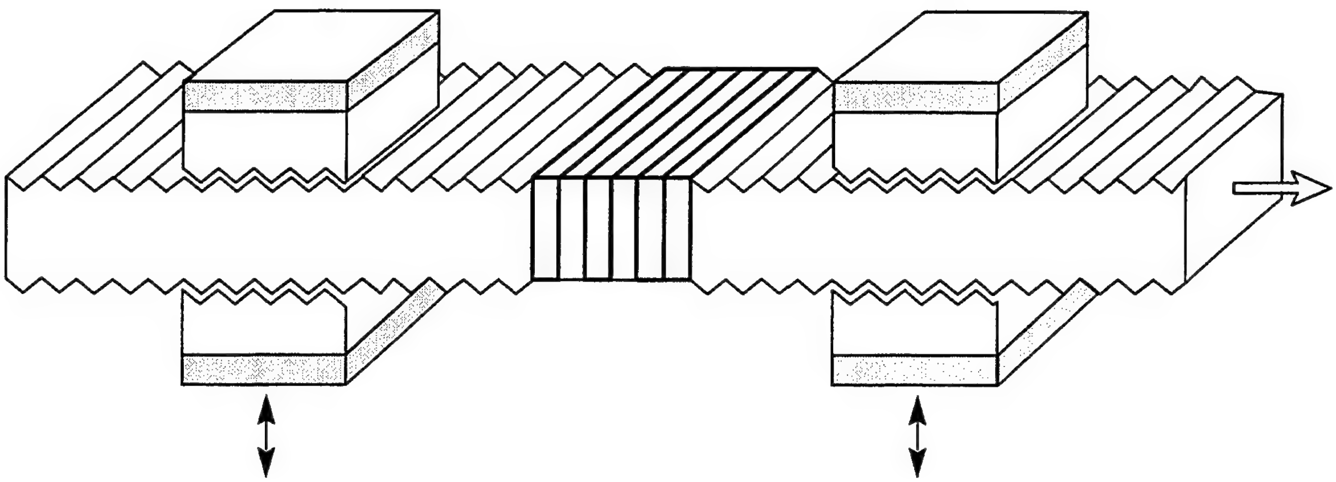
Design
Reliability ⟹ Established / Robust / $>10^4$ Cycles



Efficiency ⟹ 3%

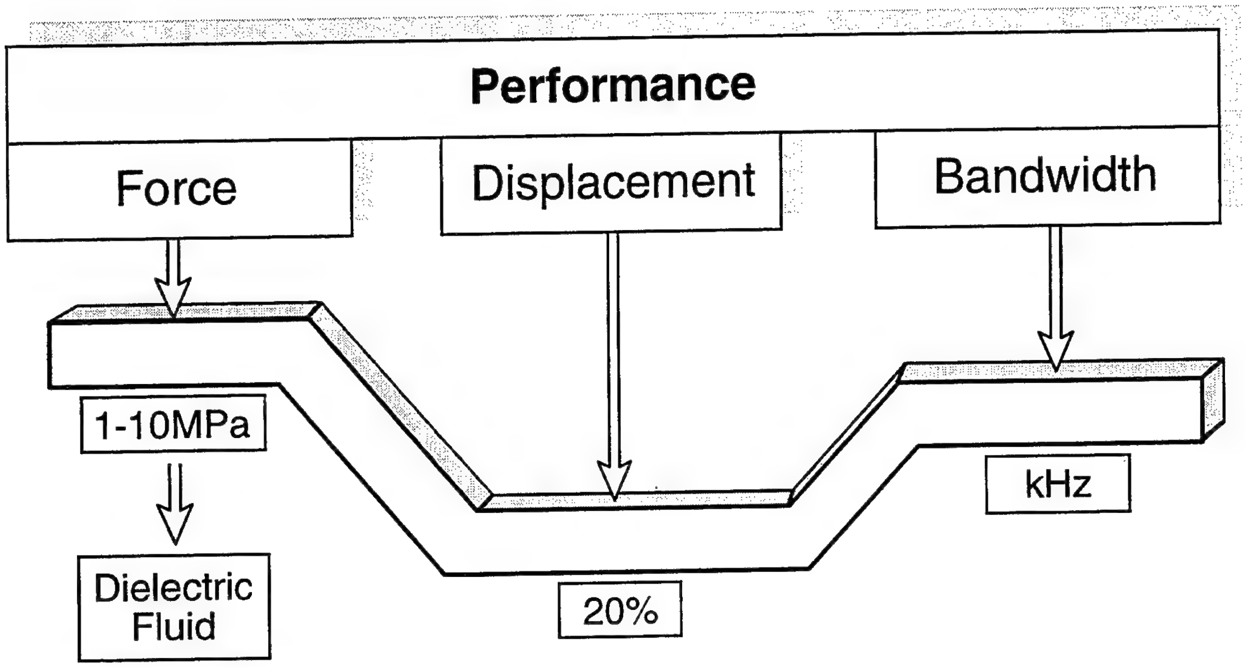

FERROELECTRICS
PZT
PNM-PT
PLZT
PSnZT
Polyurethane
Performance
Force
Displacement
Bandwidth
0.3%
10-100 MPa
New
1%
Ratchets
10%
kHz-MHz
Design
Reliability
Partial Codes
Unknown Phenomena
>10^8 Cycles
Efficiency
60%

FERROELECTRIC RATCHET



ELECTROSTATICS

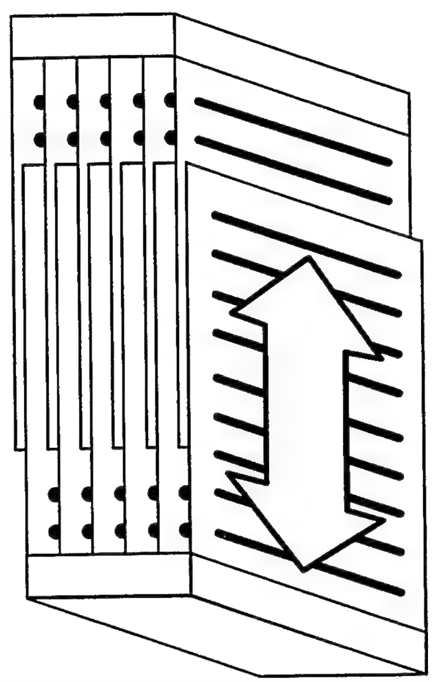
Synthetic Muscle



Design

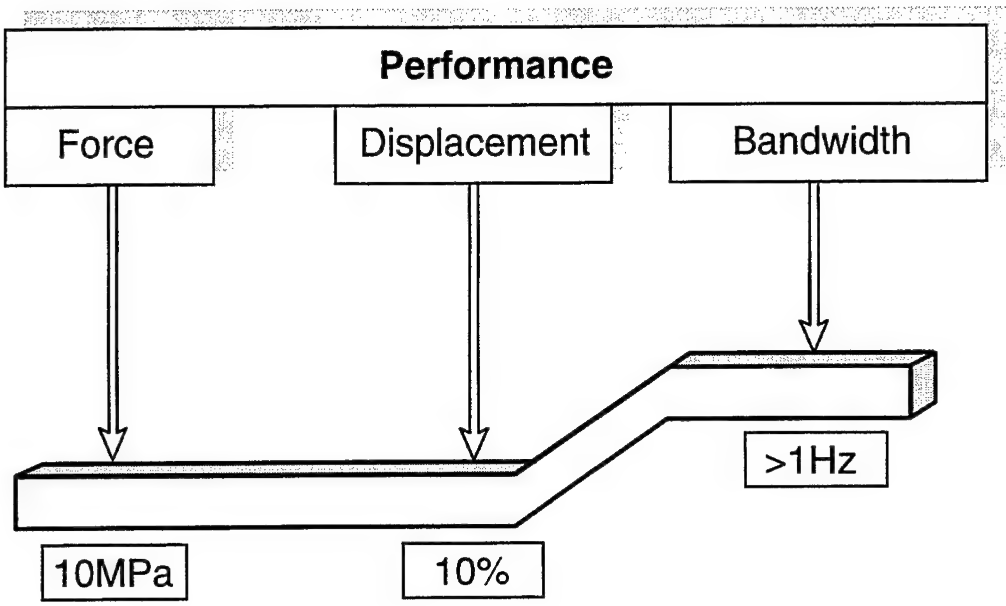
Reliability

?

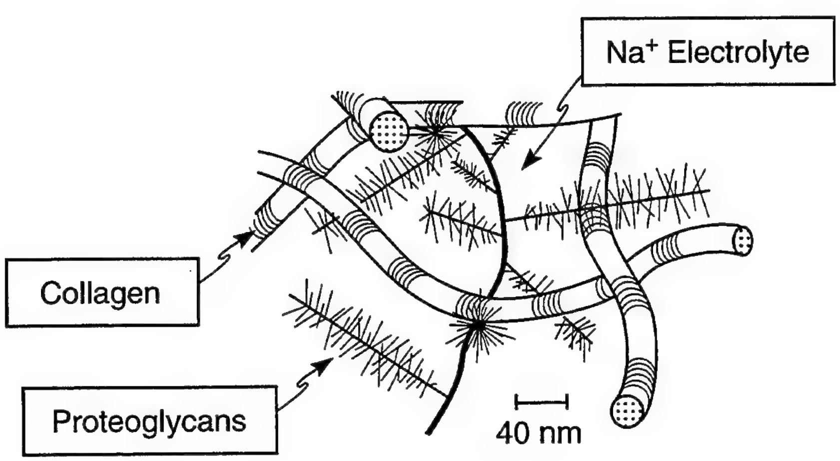


BIOMIMETICS

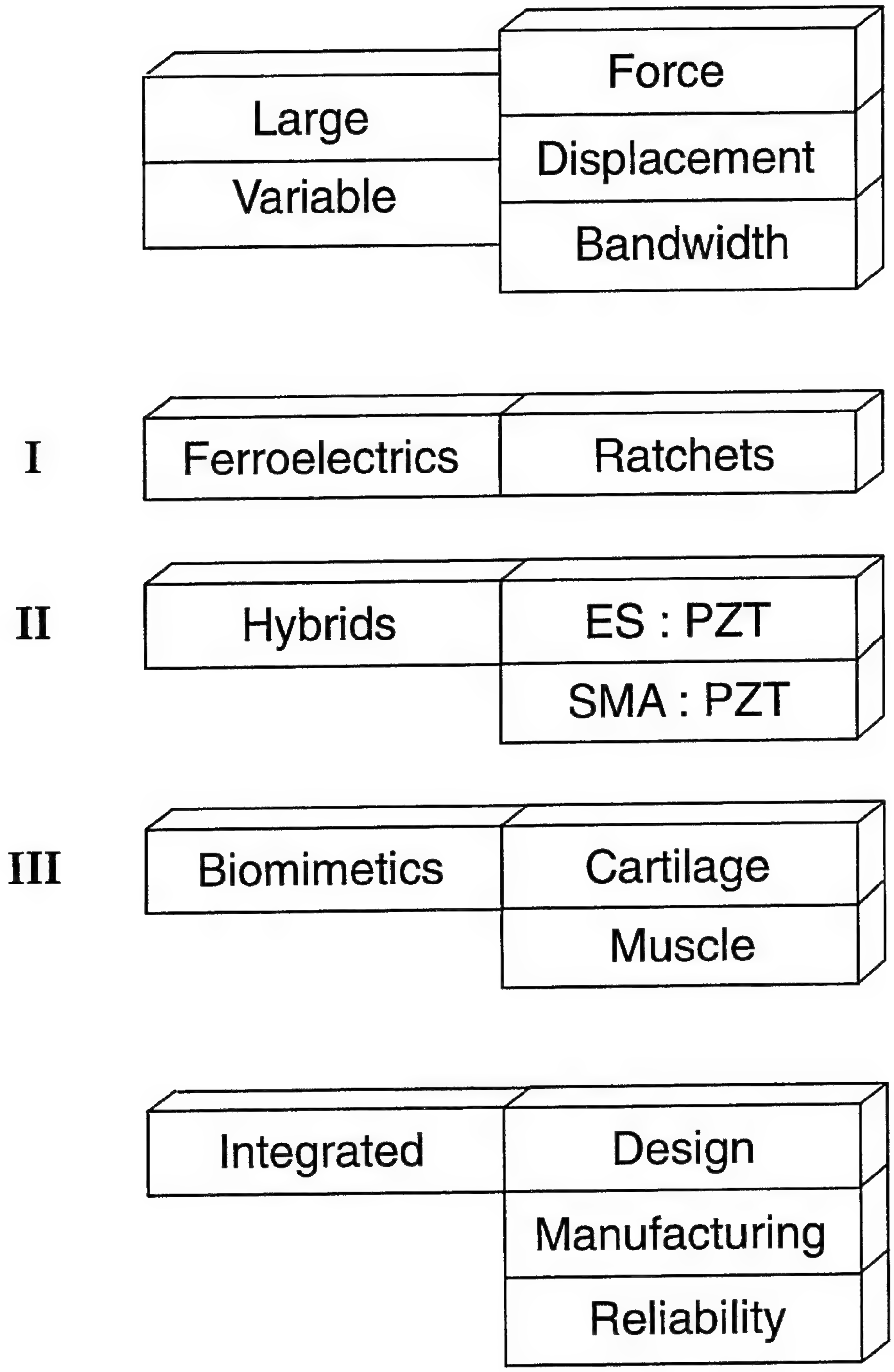
Synthetic
Cartilage



Design	⟹	Code ✓
Reliability		>50 yrs



MATERIALS/DESIGN OPPORTUNITIES



SUMMARY

New DoD Applications Limited By Strain Capacity of Solid State Acuators

- Mesomachines
- Vectoring Systems
- Medical Systems

Materials Ensemble And Design Concepts For Large Strain Developed

- Enhanced Ferroelectrics
- Biomimetics
- Hybrids

Integrate Materials And Design Concepts With DoD Applications

- Reliability
- Efficiency

IMPLICATIONS FOR DARPA

- Match Authority Requirements For Military Applications To Materials/Design Innovations

- Promote Development of High Authority Actuator Ensembles

- Combine Attributes Into Versatile Hybrid Systems

Solid State Mechanical Actuation

Workshop Organizers: E. Cross and A. Evans

July 9, 1996

8:00 a.m.	**DARPA Perspective** R. Crowe (DARPA)
8:15 a.m.	**Piezoelectric Ceramics** K. Uchino (Penn State)
8:45 a.m.	**Electrostrictive Ceramics** S. Winzer (Lockheed/Martin-Palo Alto)
9:15 a.m.	**Phase Switching Ceramics** C. Hicks (NOSCC)
9:45 a.m.	**Break**
10:15 a.m.	**Polymer Ceramic Composites** N. Hagood (MIT)
10:45 a.m.	**Magnetostrictors** J. Cullen (NSWC)
11:15 a.m.	**Shape Memory Alloys** B. Carpenter (Lockheed/Martin-Denver)
Noon	**Lunch**
1:15 p.m.	**Polyurethane Electrostrictors** Q. Zhang (Penn State)
1:45 p.m.	**Artificial Muscle** K. Higuchi (University of Tokyo)
2:15 p.m.	**Application Perspectives** D. Pearson (United Technologies)
2:45 p.m.	**Reliability Issues** A. Evans (Harvard University)
3:15 p.m.	**Discussion**
4:45 p.m.	**Adjourn**

Solid State Mechanical Actuation

July 9, 1996

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NEW BIOMATERIALS

G. Whitesides

EXECUTIVE SUMMARY

Objective

Biology is now one of the most rapidly developing areas of science. In the biological sciences, there are a range of opportunities for materials science: materials *from* biological sources with unique properties; synthetic materials *for* biological systems—that is, materials designed to operate in biological media; "designs" embodied in biological systems that suggest solutions to problems in man-made systems. This workshop surveyed opportunities in the second and third of these areas; significant parts of the first are already being covered in existing programs.

DoD Relevance

There are a range of problems that new materials and systems derived from biology might help to solve. These include:

- Technology for defense against biological weapons
- Hybrid systems that combine biological and synthetic components, for use in sensors and autonomous systems
- New types of structures of use in robotic and sensing systems.

Summary of Scientific and Technical Issues

Milan Mrksich: The Interface between Biological and Man-Made Materials. The design of the interface between man-made and biological materials and components is key to a number of hybrid systems, from protein- and cell-based sensors to implants. This interface between the biological and the synthetic is not well-defined at the molecular level. It is clear that contact of a synthetic surface with a biological medium results initially in adsorption of proteins on the surface, and that these proteins undergo a complex series of structural rearrangements as they adapt to the surface. *Designing* surfaces to control these interactions is not yet possible, although a number of tools are now available that make it possible to *study* biologically relevant processes occurring at them. This field is in its infancy, but now has the tools—surface analytical systems, microfabrication technology, molecular self-assembly—to progress rapidly.

Don Ingber: Controlling and Monitoring Cell Structure. The normal state of most mammalian cells is to be attached to something—other cells or structures in the body. Cells that detach from their supports are often abnormal in some way, and normal cells, when detached, will usually go into apoptosis (programmed cell death) after a short interval. The ability to study the influence of the chemistry and topology of the surface to which cells are attached has increased greatly as a result of methods for preparing surfaces engineered at the molecular level and micron-scale level.

The structure of the interface to which a cell is attached has been demonstrated to have a strong influence on its behavior. A class of proteins called "integrins" is key to forming patches for attachment of the cells, and attachment results in the assembly of a complex internal framework in the cell— the cytoskeleton. The cytoskeleton is interesting both for what it reveals about the way

in which the cell senses and responds to its environment, and for its suggestion of mechanical structures. The network of filaments in the cytoskeleton has been modeled in terms of the "tensional integrity" or "tensegrity" concepts of Buckminster Fuller: that is, as a network of rigid compression elements and flexible tension elements that provide overall rigidity to the structure.

Changes in cell function are modulated by mechanical stresses transmitted to cell at discrete points on its surface. These stresses can be detected by a number of clever optomechanical systems. In one, for example, it is possible to attach magnetic beads to the cell and to apply known forces to these beads through external magnetic fields. With this technique, one can measure the stiffness of the surface binding sites.

These studies of cells on surfaces are interesting for what they suggest about the structure and properties of cells, and for the suggestion that studies of cells attached to patterned surfaces and examined optically can sense the interior state of the cell. This type of system has the potential to form the basis for new classes of sensors—"effect sensors" —that use the living cell as the key sensing element. This type of sensor has been examined at the level of prototypes using neuronal cells; a much broader range of outputs is available.

Jeff Hubbel: Tissue Engineering. The ability to regenerate tissue is of potentially very great importance in aiding wound healing and increasing human performance. There has been substantial progress made in controlling the growth of *simple* tissues—that is, of collections of a *single* cell type such as skin—but the goal of growth or regrowth of more complex tissues and organs is still distant. Many factors important in understanding the factors that control this type of process—especially the extracellular matrix and growth factors—are being identified.

Van Mow: Articular Cartilage: A Paradigm for Hierarchically Structured and Multifunctional Biological Tissue. Biological systems offer a very wide range of models for functional structures. This talk summarized one functional structure: the joint of the knee. An important aspect of this structure is the cartilage: a remarkable material with superb durability and load-bearing capability. The cartilage is a complex, hierarchical structure, in which 90% of the load is born by water trapped in the pores of a complex organic gel.

The importance of this type of work is its ability to suggest fundamentally new architectures for materials and structures that may be useful to the DoD.

Barry Marrs: Enzymes from Extremeophiles. Among the most remarkable forms of life are the bacteria that live in extreme environments: "black smokers" on the sea floor, hot springs, arctic seas. There has been very little known about these species, since they have been so hard to culture. Recent advances in microbiology and molecular genetics now makes it possible to grow these organisms, and, more importantly, to extract, clone and produce enzymes from them for use in other environments. A review of this technology suggests that it is currently being directed largely toward the chemical process industry. It may have, however, direct application to problems in the DoD: For example, the availability of enzymes that operate at 100° C suggests application where high-temperature shelf-life is important: rugged field kits based on enzymatic activity; biological decontamination in hot environments; certain kinds of environmental cleanup.

Bob Ladner: Phage Display. There are a wide range of interesting proteins expressed in nature that have not been used by man. One is the so-called Kunitz domain, a very stable structure that is found in diverse organisms.

By taking advantage of the techniques of molecular genetics, it is possible to vary the structure of these proteins to accomplish a number of inhibition and recognition tasks. A key technology is "phage display." A phage is a virus that infects bacteria. It is possible to cause massive mutation in strains of phage that display Kunitz domains, and then to select the phage that shows the tightest binding to a target structure immobilized on a surface. The phage can then be replicated by growth in *E. coli*, or other suitable microorganisms.

Phage display, and other techniques that are based on generating massive genetic diversity in biological systems and selecting among the structures that are produced by some appropriate technique, are one of a number of techniques now being used that take advantage of massive parallelism to identify useful biological activities rapidly. In the particular case of Kunitz domains, there is the potential for low cost and high stability coupled with the broad diversity in activities.

Conclusions and Observations

Nature offers a very wide range of functions and structures for use in non-biological and partially biological systems. This workshop only touched on some of the aspects of this field, but within its narrow scope, applications for biological structures were apparent in a number of areas:

- **Biological Defense.** Enzymes and recognition molecules will certainly be widely used in systems for detecting, classifying and identifying biological weapons. Proteins have been considered fragile species. The new group of proteins from extremeophiles and selected, genetically engineered structures offer the potential to extend the range of conditions over which biologically derived components can function over the full range from 0-100° C. Other uses for these systems include decontamination and perhaps (for Kunitz domains, which are derived from a human protein) new types of protein antidotes.

- **Counterterrorism.** The needs for sensors and decontaminating reagents in counterterrorism overlaps significantly with that in biological defense, and there should be substantial utility for biological agents in this area also.

- **Environmental Cleanup.** Certain problems in environmental cleanup would benefit from particularly stable enzymes and new sensors.

- **Biomimetic Structures.** Examination of the knee suggests a range of materials and structures for load bearing and movement that are quite different from those used today. Examination of other functional biological structures—eyes (for sensors), kidneys (for active membrane filters), etc.—would certainly stimulate the development of new types of structures and systems. This area of research is long-term fundamental discovery work, but it is an area that has been amazingly little explored, based on its potential for suggesting new types of structures.

- **Biosensors.** Biosensors have range of uses outside of BW defense and counterterrorism: for example, as components of personal status monitors and in military medicine. The central components on which these systems are built are protein receptors. "Effect sensors"—cell-based sensors—offer a fundamentally new approach to examining influences of all sorts on living biological systems.

- **Military Medicine.** New therapies based on polypeptide antitoxins, aids to wound healing and tissue regeneration, replacement organs—all can come from examination of materials from biology, or materials obtained using combinatorial approaches.

- **Energy Production.** Stable enzymes make it possible to consider systems for supply-independent power production such as the biofuel cell.
- **Synthetic/Biological Hybrids.** A long-term future for science and technology would involve the fusion of biological and synthetic systems. Any realistic approach to this objective will involve many steps, but one crucial one that is already clear is engineering the interface between the man-made and the biological system. It is now possible to begin to think about this area of research with some optimism that the tools necessary to proceed are largely available.

Is there a Role for DARPA in Biomaterials Research? There is, at present, little federal support for biomaterials research, biological devices, and even biosensors. There is an opportunity for DARPA to lead in this area, as it has led in the past in other areas of materials science.

New BioMaterials and Interfaces

George Whitesides
Greg Kovacs

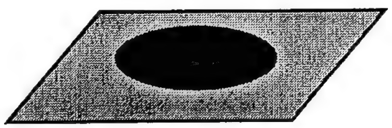
Objectives and Relevance to DoD

To explore systems from biology that provide new capabilities or concepts for the DoD:

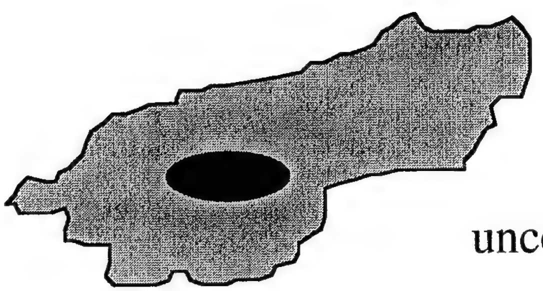
- *Hybrid Systems: biological /synthetic systems*
- *New capabilities: catalysts, sensors, recogition elements, tissues (especially for BWD and environmental cleanup; military medicine)*
- *New Concepts: sensing, movement (BWD, robotics)*
- *New Strategies: directed evolution*

Sensors and Arrays

Effect Sensors
based on cells.

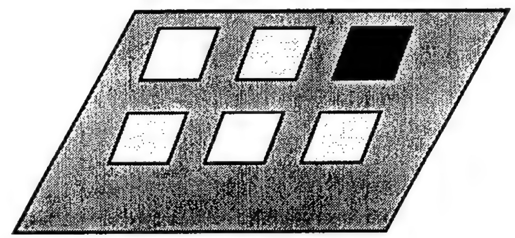


templated cell



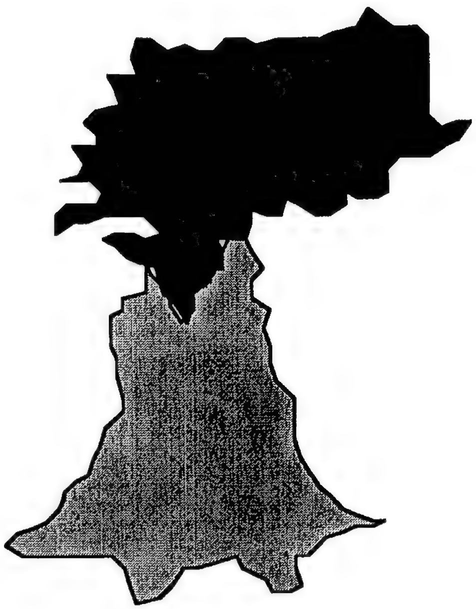
unconstrained cell

Arrays



- Sensors
- Catalyst Development
- Directed Evolution

Proteins: Extremeophiles and Kunitz Domains



Extremeophile Enzymes:

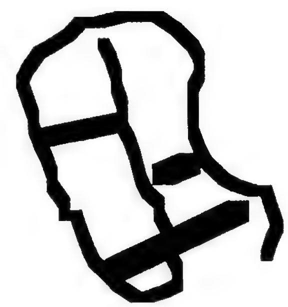
(0–100 °C stability)

Black smokers; hot springs, ..

- *BWD Decontaimination*
- *"Active Masks"*

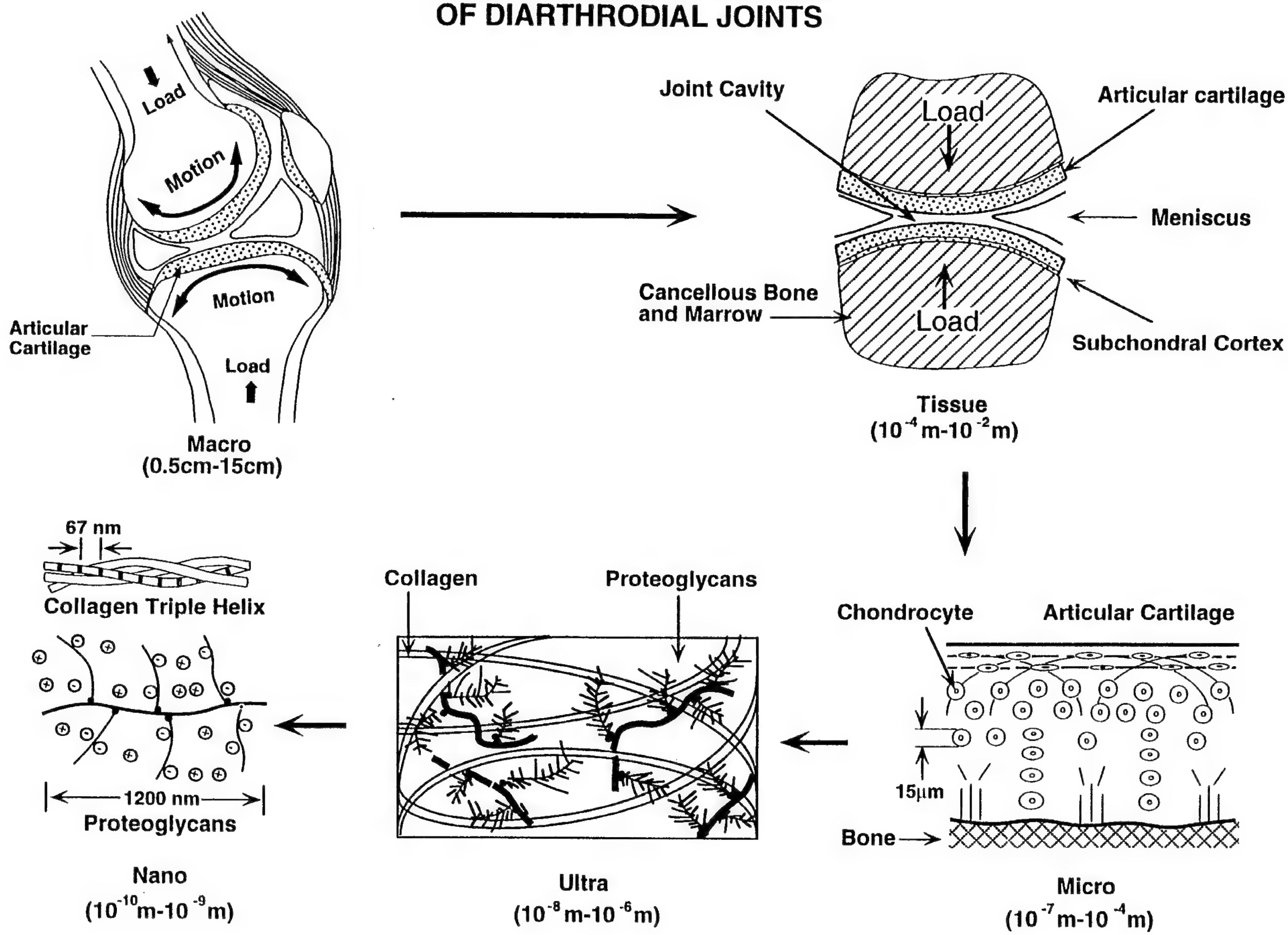
Kunitz Domains

Snake Venom
Cone Venom
Plasminogen



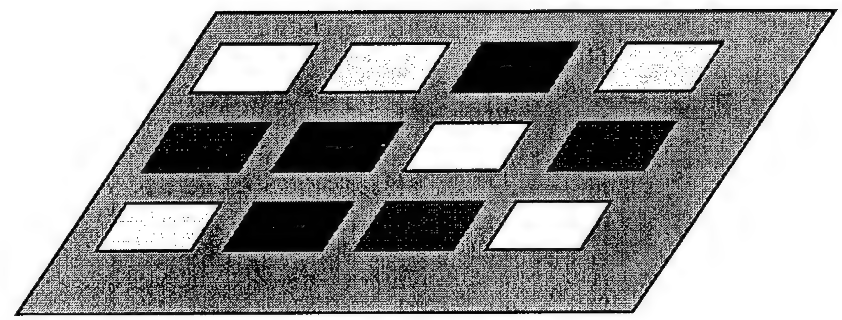
- *Low-cost sensor elements for BWD*
- *Therapeutics?*

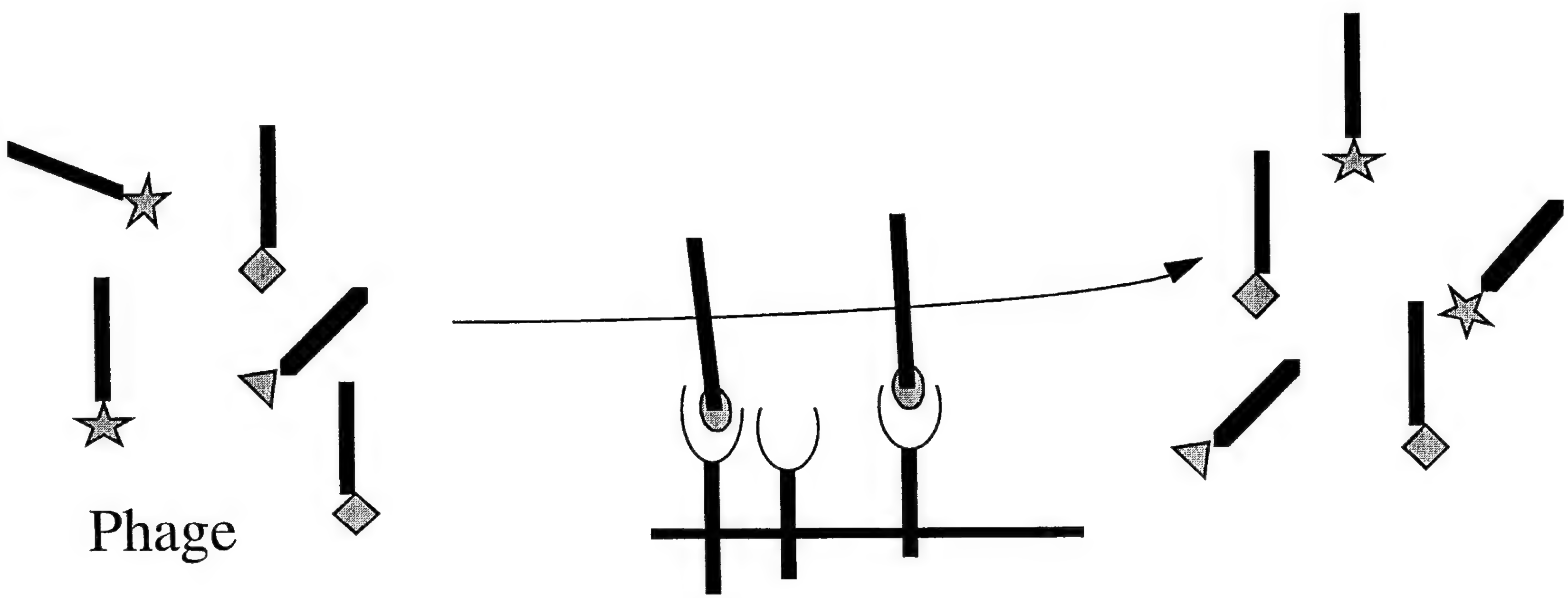
HIERARCHICAL STUCTURE OF DIARTHRODIAL JOINTS



Directed Evolution; Combinatorial Arrays; Phage Display

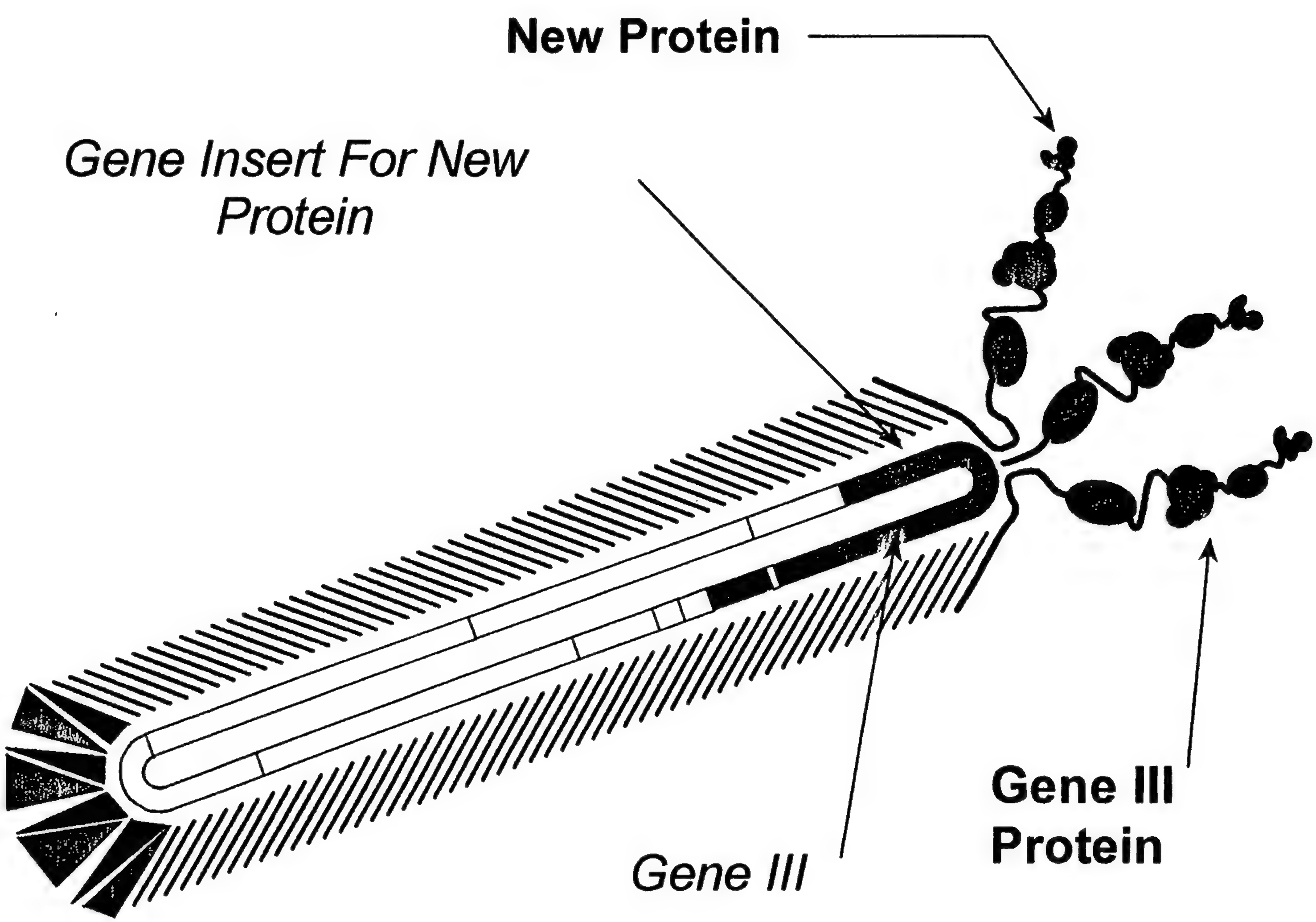
- *Efficient Screening of very Large Numbers of Samples*
- *Mutation*
- *Selection*
- *Optimization of Performance*



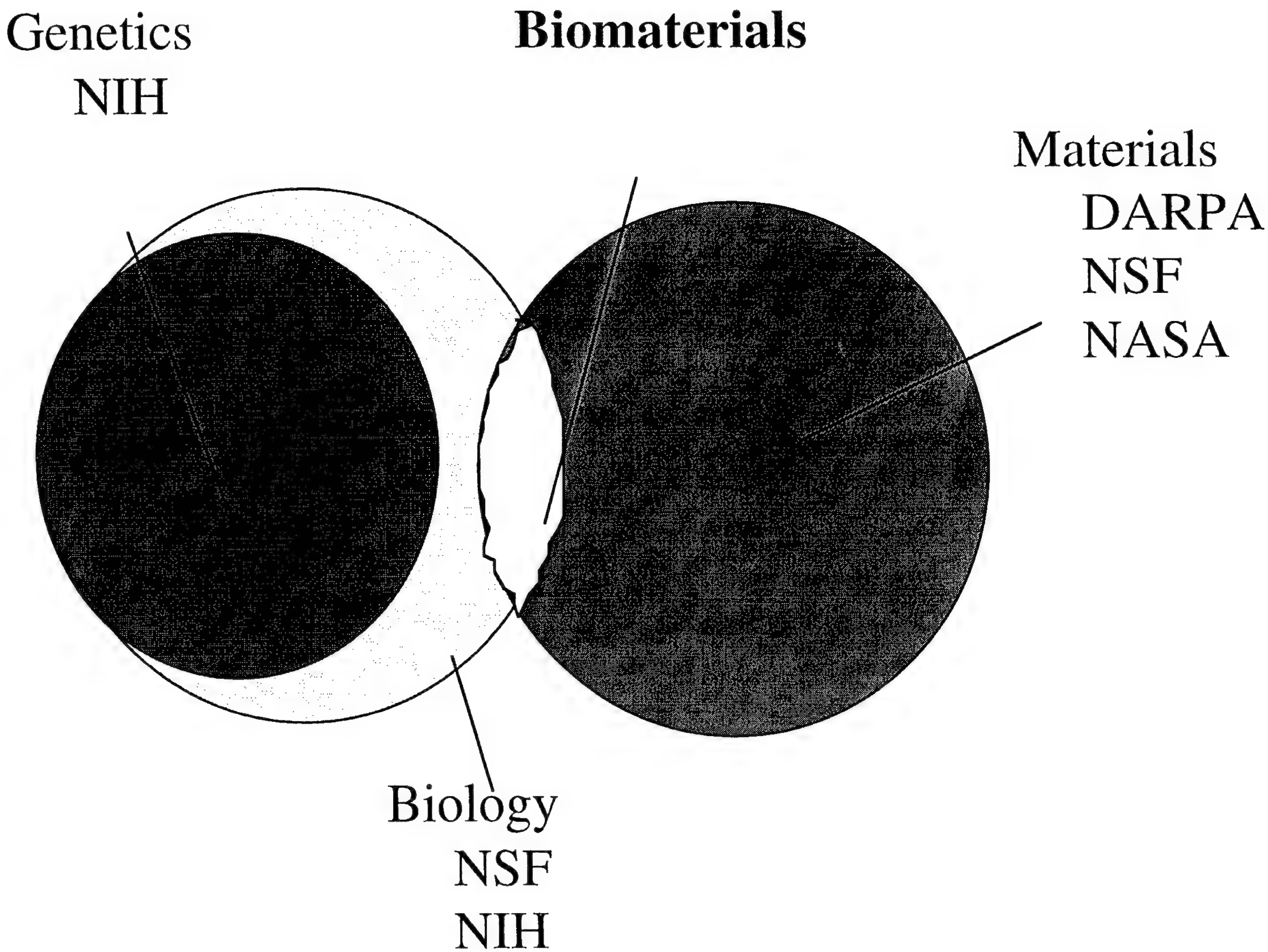


Phage Display --- Display On M13 Gene 3 Protein

Dyax Corp.



Federal Funding for BioMaterials



Conclusions

- Opportunities for engineered surfaces, proteins, cells, tissues: protein and cell ("effect") sensors for BWD, decontamination, combat medicine, ...
- New concepts: biomimetic materials and systems; directed evolution
- Big, long-term opportunity: bio/synthetic hybrids
- Opportunity to be the dominant source of support

New Bio Materials & Interfaces

Workshop Organizer: G. Whitesides

July 10, 1996

8:00 a.m.	**Introduction** George Whitesides (DSRC\Harvard))
8:15 a.m.	**The Interface between Biological and Man-Made Materials** Milan Mrksich (University of Chicago)
9:15 a.m.	**Break**
9:30 a.m.	**Controlling and Monitoring Cell Structure** Don Ingber (Children's Hospital)
10:15 a.m.	**Tissue Engineering** Jeff Hubbel (California Institute of Technology)
11:00 a.m.	**Articular Cartilage: A Paradigm for Hierarchically Structured and Multi-functional Biologic Tissues** Van Mow (Columbia University)
11:45 a.m.	**Lunch**
12:15 p.m.	**Enzymes from Extremeophiles** Barry Marrs (Recombinant BioCatalysis, Inc.)
1:15 p.m.	**PHAGE Display** Dr. Bob Ladner (DYAX)
2:00 p.m.	**Discussion**
	Adjourn

New Bio Materials Interfaces

July 10, 1996

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NANOMATERIALS

H. Ehrenreich, A. Heuer, T. McGill, R. Osgood, A. Evans and J. Hutchinson

Workshop Objectives

Nanomaterials and structures may well become increasingly important in the near-term future. A survey of the current status of the field and the promise of possible DARPA opportunities is therefore timely.

Relevance to DoD

Nanomaterials can be one-dimensional (e.g. nanotubes or ultrathin films along the direction perpendicular to the film plane), two-dimensional (e.g., ultrathin films along the planar direction), or three-dimensional (e.g., quantum dots). They can also have intermediate dimensionality (e.g., microporous materials such as zeolites that are three-dimensional but have large two-dimensional like surface areas). Technologies of importance to DoD that might benefit from the use of nanomaterials include chemical and bio-sensors and protection, nanocrystal-based memories, surface films that enhance mechanical properties and that reduce wear, fracture and corrosion, and catalytic materials that convert pathogens into less harmful molecules.

Scientific and Technological Summary

A one-day workshop devoted to the present state-of-the-art of research, development and possible applications of nanomaterials was held on July 11, 1996. Such systems are of current or potential interest in biology, physics, chemistry, and materials science. Interest in devices or structures having one or more nanodimensional size scales rests on their potential for novel physical, chemical or electrical properties, but exploitation involves significant synthetic and fabrication difficulties, particularly the assembly of nanomaterials into macroscopic structures or devices.

C. M. Lieber (Harvard) surveyed the field, emphasizing which properties could be expected to depend dramatically on size and anisotropy and focused on synthetic strategies for rational growth of one-dimensional structures, including template-mediated, VLS (vapor-liquid-solid), and VS growth.

TiC, NbC, Fe_3C, SiC, BC_x, Si, ZnO and MgO nanorods or nanotubes have all been synthesized (in some cases using commercially available carbon nanotubes (see below)) and mechanical or electrical properties characterized. Techniques of characterization are challenging and require further development. A potential application is the use of MgO nanorods self-assembled into high-temperature superconductors to increase Jc.

H. Tennent (Hyperion Corp.) reviewed one of the few current near-commercial activities in this field, catalytically grown carbon nanotubules. These materials, 10 nm diameter and 10 mm long, are produced with a mass density of 0.05 gm/cc (of carbon) and surface area of 300 m^2/g. These materials are now produced in quantities of 3 kg/hr and could, if demand was at the level of 10^6 kg/yr, be available at a cost of \$2/lb. The task, now that the synthesis of production quantities of these nanotubules is in hand, is to develop fabrication technologies to exploit the unusual properties. Current activities include attempts to incorporate the tubules as reinforcements for polymer-based composites, as catalyst supports, and in various electrical applications, including batteries, thin CRTs, and as supercapacitators. In this latter application, capacitances of 120 F/gm have been achieved, which can be compared with a target value of 250 F/gm for applications in electric vehicles.

A. K. Cheetham (UC Santa Barbara) reviewed the field of zeolites (framework silicate, aluminosilicates, phosphates, and related crystalline materials), which have channels whose diameter can be systematically varied from ~0.2 to 1.3 nm. These materials have historically been used in hydrated form for ion-exchange applications (detergents, water softeners, radwaste remediation) and in dehydrated form for molecular sieving (N_2/O_2 separation, drying agents, separation of HFCs) and catalysis (gasoline production, organic isomerization, denox reactions). Recent synthetic breakthroughs have led to the production of so-called mesoporous zeolitic materials, which contain channels up to 10 nm in diameter possessing translational symmetry and separated by amorphous walls or struts. Current synthesis methods are focused on producing transition-metal-containing zeolites, leading to the hope that future optical and electrical applications may be possible.

There may be significant DoD applications for zeolites. Commercial air separators based on zeolites are widely used for factories requiring small to medium quantities of oxygen (distillation of liquid air is cost effective only for large factories requiring large quantities of oxygen). It may be straightforward to adapt such systems for battlefield applications; for example, novel gas masks based on preferential transport of common gases (O_2, N_2, H_2O, CO_2) may be possible.

Secondly, since the channel size of zeolites can be "designed" quite precisely, zeolites may find applications in defense against CBW. For example, they might be used to trap certain species and then catalytically oxidize or otherwise transform the agents into harmless moities.

S. Tiwari (IBM Watson Research Center) discussed the use of single electron effects in the limits of miniaturization of silicon nanocrystal memories. He suggested that solutions for areal scaling and the power and density limitations of DRAMs can be achieved by using nanoncrystals. Further, he believes the advantage of multidimensional confinement and single electron effects with power and density gains are clear for 300 K nanocrystal memories. However, the technological achievement of single electron memory (and logic) in these limits will require painstaking work and accurate modeling not based on fitting parameters or speculation. Small-scale demonstrations that confirm scalability to larger integration are also necessary. However, success will result in giga-terabit memories coupled to a 100 million transistor logic.

A typical candidate nanocrystal would have dimensions of 3 nm. The associated Coulomb energy associated with an electron in a crystal of that size is sufficiently larger than kT at room temperature that 10% variations in size or oxide thickness are consistent with single electron storage. One electron storage yields a threshold shift of 0.25 eV. A 0.18 x 0.25 mm memory element contains about 450 nanocrystals, a sufficiently large number to keep statistical fluctuations small. The time constants are long, but sufficient for memory applications. For example, a 1.6 nm oxide thickness requires 200 ns and 3 V under "write" conditions, producing a threshold shift of about 0.65 V. The retention time is about a week at room temperature. The element is robust with a high cyclability rate.

Single electron tunneling transistors (SETs), discussed by S. Y. Chou (University of Minnesota), have been of considerable research interest during the past few years and have led to a great deal of new physics. However, since each circuit element relies on single electron operation, their technological implementation is far more difficult and hence much further in the future than the proposals for silicon nanocrystals such as that of Tiwari, which involve currents and voltages not too different from those in current use. Chou justified fundamental investigations dealing with charging and quantum mechanical effects as a function of size scale on the grounds that both single electron and quantum effects will become important as gate lengths are reduced below 100 nm and that they will be dominant below 10 nm. He inferred from a linear extrapolation that the number of electrons per bit will have been reduced from 10^3 at present to less than 10 by the year 2020. A rapid development of room temperature SET memories is projected, as is a near term demonstration of room temperature Si devices, a thorough

investigation of single electron and quantum effects in conventional transistors, and the development of new structures. He envisions the development of sub-50 nm nanolithographies (e-beam, X-ray, STM, nano-imprint, etc.), nanoscale control in material deposition and etching, and the utilization of new nanomaterials based on polymers, smart substrates and various kinds of hybrids. Finally he anticipates the development of new methods in manipulating materials based on self-assembly and other novel approaches that are currently under investigation. Aside from nano-imprint lithography, which Chou and collaborators recently demonstrated, these projections of future developments were not documented.

The presentation of A. P. Alivisatos (UC Berkeley) focused on the physical properties of 2–20 nm crystals of CdSe, CdS, InP, InAs, and Si whose surface is terminated with organic ligands. These quantum confined systems permit the control of physical properties such as optical absorption, electroluminescence and structural phase transitions by size adjustments. These studies are important because the structures in question lie in an intermediate region in which they can exhibit either molecular or solid state properties. Blends of the inorganic nanocrystals embedded in organic polymer semiconductors results in new materials whose properties can be tailored.

The materials synthesis is unconventional in that nucleation and growth are separated into two distinct steps, a key to obtaining monodispersed samples. A nano-crystal of diameter ~8 nm is required to achieve the band gap characteristic of the solid. The evolution of the optical spectra provides insight into the character of the gradual molecular to solid transition. Properties such as photoluminescence and photoconductivity are also strongly affected by the organic (e.g. the semiconducting polymer MEH PPV) coating surrounding the inorganic nanocrystal in part because of charge or dipole-dipole (Forster) energy transfer between the two. These properties may possibly be exploited for LED and PV devices by utilizing, for example, CdSe/MEH PPV blends. Other optical device applications will be enabled if such nanocrystals can be made to have uniform size and can be embedded in a wider variety of materials.

Alivisatos also described single nanocrystal tunneling between Au tips, the organization of 14 nm Au nanocrystals using nucleic acids, and structural transformations in semiconductor nanocrystals.

Conclusions and Observations

Nanomaterials often have unusual and useful physical, chemical and electronic properties. A variety of synthetic techniques exist for their fabrication but assembly into meso or macroscopic structures of devices remain to be developed. The pathway to technological exploitation is most obvious in electronics, where single electron effects are the obvious extension to current VLSI developments. Structural application of nanomaterials remain appealing but with a few exceptions have not yet been realized, in part because of the difficulty of fabricating macroscopic components in a cost effective manner. Chemical applications, for example using zeolites, appear to offer some near-term benefits. In summary:

- Zeolites and other chemically interesting nanomaterials may offer some near-term DoD applications (O_2 generation, CBW defense). In many cases, these would take a different form than that conventionally used for zeolites; i.e., instead of being in granular or particulate form, the zeolites might be used as thin films (for sensors, for example), or in composite form, where the matrix would provide structural integrity.

- Structural applications of nanomaterials with DoD relevance are attractive but remain elusive.

- Silicon nano-crystalline electronic memories are progressing and may find application if thin SiO_2 gate oxides can be made sufficiently insulating. The systems incorporating them may be sufficiently different, that design including the appropriate interconnects, etc., should be given consideration.

Nanomaterials

H. Ehrenreich, A.H. Heuer,
A. Evans, J.H. Hutchinson,
T.C. McGill, R.M. Osgood

Objective

To assess the current status and use of nanomaterials and the promise of possible DARPA opportunities.

Relevance to DoD

Applications to:

- Chemical/biological sensors and protection
- Electronic memories
- Mechanical property enhancing surface films
- Catalytic materials for pathogen conversion

Nanomaterials/ Nanostructures

- **Defined by sizes: one or more dimensions are 1–100 nm**
  - 1-dimension: 2D planar structures
  - 2-dimension: 1D rod/wire/tube structures
  - 3-dimension: 0D cluster/dot structures
  - "2.5"-dimension: Nanoporous materials (Zeolites)

- **Comprise systems found in biology, physics, chemistry**
  - Biology: e.g. muscles, molecular motors
  - Chemistry: nanotubules, nanoporous solids
  - Physics: 2 DEG in MOSFETs, single electron transistors

Carbon Nanotubules

- **Characteristics**
  - Diameter ~10 nanometers
  - Length ~100 millimeters
  - Surface area ~300 m^2/g
  - Mass density ~.05 g/cc of carbon

- **Available in production quantities**
  - Now produced at 3 kg/hour at $20/lb
  - With demand level of 10^6 kg/year at $2/lb

- **Possible uses**
  - Reinforcement for polymer based composites
  - Catalyst supports for metal particles
  - Efficient battery electrodes
  - Flat cathode ray tubes:
    addressable pixels of vertically aligned fibrils
  - Supercapacitors

Microporous Framework Structures

- **Characteristics**
  - Cavities and channels of molecular dimensions
  - Zeolitic Materials

Periodic Structure	6–20 rings
Window sizes	2–13 Å

  - Mesopores

    Translational symmetry, amorphous walls

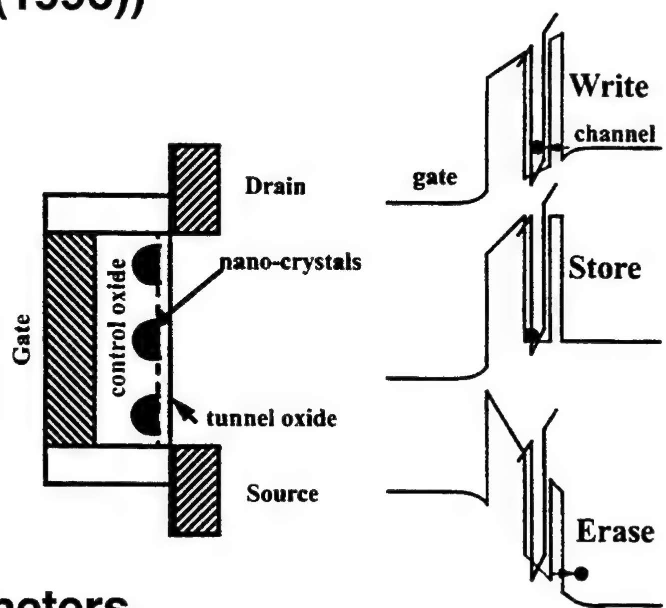
    Window sizes up to 100Å

- **Uses**
  - Molecular sieving
  - Catalysis

- **Possibly significant DoD applications**
  - Gas masks using preferential transport of common gas (O_2, N_2, H_2O, CO_2)
  - Tailored zeolites for defense against CBW: trap dangerous species and convert catalytically.

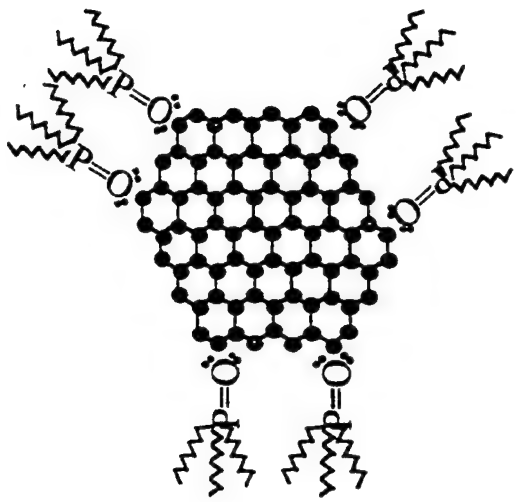
Nanocrystal Based Memories

- **One-electron devices**
- **S. Tiwari's proposal (Appl. Phys. Lett. <u>68</u>, 1377 (1996))**



- **Parameters**
  - 450 nano-crystals per MOSFET (~0.18 μm)
  - Nanocrystal dimensions ~5 nm, separation ~5 nm
  - Nanocrystal density ~10^{12} cm^{-2}
  - Control oxide ~7 nm
  - Threshold shift ~0.36 V for one electron per nanocrystal

Semiconductor Nanocrystals



- 20 to 200 Å in diameter.
- Crystalline core.
- Surface terminated with organic ligands.
- Materials: CdSe, CdS, InP, InAs, Si.

What's interesting?

- Control of physical properties with size:
  - ➡ Optical: absorption and emission.
  - ➡ Electro-optical: electroluminescence.
  - ➡ Structural: phase transitions.
- Quantum confined systems.
- Applications:
  - ➡ LEDs, solar cells, nonlinear optical materials.
- Transition between molecular and solid state regimes.

Conclusions

- Nanomaterials may be important to some long-term technologies, and DARPA should monitor progress.
- Thin film zeolites and other chemically interesting nanomaterials may offer some near term DoD applications (e.g. O_2 generation, CBW defense). Structural reinforcement by porous backing material requires attention.
- Silicon nano-crystalline electronic memories are progressing and may find application if thin SiO_2 films can be made sufficiently insulating. New systems requirements need examination.
- Controlled size semiconductor nanoparticles embedded in an appropriate matrix may yield novel optical applications.
- Structural applications of nanomaterials with DoD relevance are attractive but remain elusive.

Nanomaterials

Workshop Organizers: A. Heuer and H. Ehrenreich

July 11, 1996

8:30 a.m.	**Introduction** Steve Wax or Xan Alexander (DARPA)
8:40 a.m.	**Nanomaterials: Present and Future Opportunities for Research and Technology** Charles M. Lieber (Harvard)
9:30 a.m.	**Catalytically Grown Carbon Nanotubes: Synthesis and Possible Applications** Howard Tennent (Hyperion)
10:20 a.m.	Break
10:40 a.m.	**Nanoporous Materials** Anthony K. Cheetham (Univ. of California, Santa Barbara)
11:30 a.m.	**Discussion**
Noon	**Lunch**
1:00 p.m.	**Nano-Crystal Memories: Use of Single Electron Effects in the Limits of Miniaturization** Sandip Tiwari (IBM)
1:50 p.m.	**Silicon Single-Electron Quantum-Dot Transistors—Where We Are and Where We Are Going** Stephen Y. Chou (Univ. of Minnesota)
2:30 p.m.	**Nanomaterials: New Materials Through Control of Size** A. Paul Alivisatos (Berkeley)
3:10 p.m.	**Discussion**
4:45 p.m.	**Adjourn**

Nanomaterials

July 11, 1996

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ADVANCED TECHNOLOGIES FOR DEFENSE AGAINST BIOLOGICAL WARFARE AGENTS

G. Whitesides, G. Kovacs

EXECUTIVE SUMMARY

Objective

The objective of this workshop was to explore technology to assist in defense against biological weapons. The workshop included an overview of the threat and current DoD response, of bacterial pathogenicity, of advanced analytical systems, and of the unique role of the venture capital/small biotechnology startup company as a source of advanced technology in biomedicine.

DoD Relevance

Defense against biological weapons is a very important problem for the nation. The rapid pace of scientific development in many areas of advanced biology, combined with the relatively low level of scientific and technical expertise and capital investment required to produce and deliver biological weapons, makes them potentially attractive to a wide range of state and non-state adversaries of the United States. The threat covers the full range, from strategic threats against the civilian population of the United States and its allies, through threats to trained, equipped combat troops, to terrorist threats from non-state organizations and from deranged individuals.

The threat of biological weapons is widely recognized as an important one: finding counters to the many components of that threat is one of the major challenges now facing the DoD.

Summary of Scientific and Technical Issues

Ted Prociv (Deputy Assistant for Chemical and Biological Matters): The DoD Biological Warfare (BW) Defense Program.

Dr. Prociv provided an overview of the current perception of threat, and of some aspects of the U.S. response to this threat. Some of the major technical aspects of this presentation are these:

Mission Statement: The mission statement of the Medical Biological Defense Programs is to preserve combat effectiveness by timely provision of medical countermeasures in response to joint service biological warfare defense requirements and threats due to validated biological warfare agents.

This mission statement frames one part of the problem. This statement has a clear focus on *combat effectiveness* and on *validated threats*. The range of threats is, of course, substantially broader than can be covered by this focused statement, and the most attractive opportunities for investment would be those that would contribute directly to this statement, and also had the potential for value in other parts of the problem. The issue of *validated* threats is also complicated, since biological warfare, almost uniquely, offers the potential for the covert development of new types of weapons which could be validated only after their use.

Current threats and relevant research supported by the DoD include:

- Venezuelan equine encephalomyelitis - an attenuated virus based on a full-length DNA clone is being constructed.
- Brucella—an attenuated mutant strain stimulates immune response.
- Anthrax—an improved vaccine will be available in FY 96
- Botulinum Toxin—recombinant technology is being used to develop drugs to inhibit the effects of the toxin.
- Plague—a new vaccine is being developed
- Ricin—a toxoid vaccine is in advanced development
- Staphylococcus enterotoxin—a toxoid vaccine is being developed
- VEE, WEE, EEE—infectious, attenuated clones are being developed for use in vaccination.
- Vaccines and antitoxins—a range of activities directed to new vaccines and antitoxins for anthrax, plague, smallpox, VEE, botulinum toxin etc., are being developed.

The development of reliable commercial sources of vaccines and antitoxins for DoD use is requiring substantial innovation in contractual arrangements, since many healthcare companies are not interested in working on these problems or with the DoD.

Agreeing on vaccination schedules, and the populations to be vaccinated, both are subjects of continuing discussion.

Other components of the DoD effort are these:

- Medical Information systems are being developed to aid in diagnostics, treatment and education; the databases to support these systems still need to be designed and constructed.
- Masks and passive protection are based on CW gear. There is substantial need for innovation in passive or enhanced passive protection systems, especially against respiratory threats. Disposable masks may also be useful.
- Point detection systems—BIDS, CAM, IBAD—are now being fielded. There are substantial unfilled needs in all aspects of detection.

These activities provide a strong start in moving the U.S. toward a state of advanced preparedness in BWD, but there remain major opportunities to improve preparedness against biological threats. Current plans do not anticipate "hardened, ready-to-go-to-war systems" before 2010, and the more complex problem of protecting "unprotected" populations against BW threats is just beginning.

Peter O'Hanley (Stanford) Virulence.

Virulence (from the Latin word for poisonous) is the ability of an organism to cause disease in a particular host. Microbial virulence results from cumulative impact of one or several special properties, or virulence factors, which distinguish potential pathogens from harmless microbes. The practical goals of investigations into the virulence properties of any pathogen is the development of specific interventions that are anti-virulence factor.

In the particular case of a clinically relevant model system—uropathogenic *E. Coli*—a number of steps have been identified at the molecular level that influence pathogenicity. These (together with determinants and host defenses) include:

- adherence of the pathogen to the target tissues (pili/afimbrial adhesins ; urine flow, urinary antibodies, antibodies, sugar/protein moieties)

- **colonization/proliferation** (needs iron) (aerobactin; outer membrane proteins, low urinary iron, transferrin)
- **cellular injury** (alpha-hemolysin, lipopolysaccharide; urinary and parenchymal antibodies
- **cellular invasion** (cytotoxic nectrotizing factor 1; urinary and parynchymal antibodies)
- **dissemination** (serum resistance, IgA protease, capsular polysaccharide (K-antigen); phagocytes, antibodies, and antibodies + complement)

This set of factors contributing to virulence is a fairly common sequence for a subset of bacterial pathogens (including important respiratory pathogens), and suggests that it would be profitable to search for commonalities among classes of pathogens that might lead to broad-spectrum countermeasures. It is not probable that there will be any *universal* countermeasures that will include all bacteria, viruses, rickettsia and toxins, but molecular genetics is rapidly clarifying the genetic mechanisms of virulence, with the implication of more commonality than has been apparent in the past. A plausible, broad-spectrum approach to BW countermeasures might target thoughtfully chosen steps common to a number of pathogens (for example, adhesion to target tissues for both viruses and bacteria; expression of virulence-associated proteins in Gram-negative bacteria). Any single component of this strategy might not cover *all* pathogens, but some tractable number might handle *most* pathogens (of a class), and importantly, focus selectively on those components that are harmful. A successful approach of this type might mitigate one of the most serious future threats: that is, strains of pathogen genetically engineered to be multiply drug resistant (a result relatively easily obtained by putting drug resistance genes into the bacterial genome); if the toxins produced by these bacteria were ineffective, or if toxin production could be inhibited, they would be rendered relatively harmless.

The research needed to generate a solid base of information about mechanisms of virulence and pathogenicity is well understood. It can be labor intensive, but is relatively inexpensive. For example, it is necessary to isolate the virulence factors in quantities sufficient for study. It is possible to engineer organisms so that they themselves produce these materials in quantities, and shed them into solution, and the genetic techniques necessary for this type of work are now well understood.

The molecular species associated with virulence are also those required in some approaches to the development of vaccines. (All work on vaccines would first be carried out in animal models, and the development of appropriate animals–that is, those with appropriate trophic factors expressed on their cells—is itself an important part of research in this area, and would be a vital enabling technology). The proteins associated with virulence would also provide a starting point for the synthesis of peptides (e.g. fragments of virulence factors rather then the entire factors) and a demonstration of the efficacy of their effectiveness in protecting against infection. There are also other more empirical approaches to the development of vaccines. One is the semi-rational approach to the development of live vaccines: that is, start with the pathogen, mutagenize various metabolic pathways in the organism so that it dies after a few replications due to some metabolic blockade, and innoculate with this weakened species. This strategy might be improved by inserting the interleukin gene into the chromosome of the organism to stimulate the immune response by releasing small amounts of interleukin.

It is clear that the development of a rational approach to pathogenic organisms is a rich field for modern molecular biology. The tools to advance this type of research and development did not exist a few years ago, and this approach is one that offers a new avenue for BWD.

Mike Oldstone (Scripps Research Center) Viruses as Plagues

Viruses have caused plagues in the past, and studying them is key to understanding the threat for the future. The most memorable aspect of the discussions of Dr. Oldstone were his account of the numbers of deaths that have resulted from certain epidemics, and the influence of these epidemics on the course of history. For example, for smallpox and influenza, abbreviated histories of the disease include these features:

Smallpox

- 16th century: important in the history of conquest of Mexico and Peru
- 18th century: smallpox decimated the native American Indians, and was key to the rate of conquest of the new world.
- 19th century: smallpox was a key element in the death toll of the Franco-Prussian War
- 20th century: smallpox has killed 300,000,000 people—3 times more than all wars ever fought. Smallpox is now eradicated using living, attenuated vaccine. Since man is the only reservoir, vaccination *can* provide an effective strategy.

Influenza

- The 1918–1919 epidemic killed 20–40,000,000 people; 85% of deaths in American Expeditionary force were from influenza virus (WW I).

Any strategy for immunization against viral disease needs to take into account cell-mediated and humoral immunity. Variations in the major histocompatibility complex (MHC) among individuals may make generation of cell-mediated immunity difficult, but there is hope that targeting the most widely distributed MHC types will cover a large part of the population.

Attenuated viruses used as vaccines provide larger antigenic load and have been more broadly successful than other types of vaccines for viral disease.

Lee Hood (U. Washington) Advanced Techniques for Genetic Identification

Dr. Hood addressed the problem of detection and identification of pathogenic microbes in complex mixtures. The suggested strategy centered around the use of ribosomal RNA. The ribosomal RNA's evolve slowly, and therefore provide a "bacterial phylogenic tree" that can be used to sort organisms efficiently. The strategy would be to use a series of probes to target increasingly specific parts of this tree.

The key technological requirement for success in this type of scheme is to develop efficient, parallel, miniaturized arrays of probes. DNA arrays, coupled with rapid synthetic methods on a chip, offer the potential for achieving the speed and parallelism required for this type of analysis.

Examples of the throughput of technology now being developed:

- A system for nucleic acid sequencing based on capillary electrophoresis uses 1 micro-liter volumes and achieves a 10^6-fold amplification (by PCR) in 10 minutes; this system has an output of 8000 samples/8 hour shift.
- DNA probe arrays combining 100 micron features, combinatorial DN microscale DNA synthesis (by pulsed jet or photolithographic microscale hybridization assays) can give the high sensitivity and high resolution required for large-scale, rapid analyses. The DNA synthetic scheme has been prototyped with glass or silicon substrates: 100 micron

features, hydrophobic wells to help locate drops, a commercial ink-jet printing system with 20 delivery tubes, 49 pL delivery per drop, 5000 drop/second rate per head. The planned output from a 6-head system would be (by the end of 1996) 28 wafers with 150,000 20-mers of DNA per day.

Hood identified work on advanced detection and sample preparation as being the highest priorities in this field that were not receiving adequate commercial interest at present.

Tony Sinskey (MIT) Bioengineering

Professor Sinskey outlined the operation of a biomanufacturing process, and identified key areas where outside intervention might cause problems in manufacturing; these include contaminating the water supply with heavy metals, surfactants, azides and other species. He was not optimistic about the potential for identifying fermentation facilities based on other signatures.

Dick Smith (Pacific Northwest Laboratory) High-Resolution Mass Spectroscopy for Protein Analysis

Most of bioanalytical research has focused on the power of PCR and related techniques in nucleic acid chemistry. The requirement of BWD for information-rich techniques to enable the rapid identification of threats makes it attractive to look for other systems that have high throughput, and that can in principle be used to provide the input to pattern recognition systems. One very promising technique is mass spectrometry. This technique is undergoing explosive development, and promises to be one of the most widely used of the bioanalytical techniques in the next years.

There are a broad range of technology choices for both ionization and analysis. Both electrospray ionization (ESI) and matrix-assisted laser desorption ionization (MALDI) are suitable for biomolecules including complete proteins; ion cyclotron and quadrupole are competing options for the ion trap and analyzer. For MS, femptomole sensitivity is routine, attomole demonstrated, and high zeptomole (10^{-22} = 602 molecules) has been achieved.

A key need—as with all analytical methods—is to identify the front-end technologies: sample preparation and introduction;microfuidic systems.

An exciting new technique that illustrates the power of the technique for analysis of proteins involve automated selective ion accumulation for dynamic range expansion. This technique allows one to pick a portion of the mass spectrum and fill up the ion trap with that portion of the ion population. Selected ions can then be amplified by removing ions that do not occur at specific frequencies. This technique is effectively a "preparative" use of mass spectrometry.

It is also now possible to use bioaffinity methods with MS: electrospray preserves noncovalent molecular interactions including protein-protein complexes, and it is possible to use these interactions in the vapor phase for analysis.

The conclusion from this analysis is that modern MS methods offer the potential to provide confident BW detection/identification in some circumstances in 2–15 min. An important need is rapid front-end sample processing. Ion traps and electrospray are the best approaches to biomolecules; improved computer/control will help speed analysis. Substantial reduction in instrument size should be feasible.

Jim Tananbaum (Sierra Ventures) How the Biotechnology Industry Works.

Dr. Tananbaum discussed the relationship between the healthcare industry and the venture capital business, with an eye to developing better relations with the DoD in key areas of interest in BWD. The key opportunity in terms of windows for finance is early in the development cycle

for biotechnology companies: that is, before successful prototypes of technologies have been developed, and the cost of capital through the classical sources is either very expensive (venture capital) or unavailable (investment banking). From the vantage of the company, this is the time to develop technology to a level that makes corporate validation possible and increases valuation. The interest in the DoD is typically not to develop a general area of technology, but rather to develop specific technologies or products that satisfy needs. There is, therefore, an intrinsic difference in objectives, and this difference is one factor contributing to the difficulty in finding effective relationships between the DoD and the world of small biotechnology companies in areas related to BWD.

There is also a difference in style of company favored by VCs and by the DoD. The venture market tends to favor technology platforms: in these companies, early investors may have exit points before true proof of principal, at values based on industry potential. The DoD tends to be interested in products, and product companies favor late investors/partners, and only have exit points after proof of principal, and value based on cash flow potential.

Conclusions and Observations

Biotechnology is rich area for investment. The key issues are to develop strategies that provide technologies relevant to working systems, and address plausible future needs in an area of warfare in which science is providing great opportunity for invention to developers of offensive weapons and in which the U.S. has no offensive capability.

Opportunities

There are a number of areas that offer opportunities for significant contribution.

Molecular Basis for Disease. The ability to separate the influences of a pathogen on man into well understood and characterized molecular components offers the capability to approach the development of vaccines, antidotes, therapeutics, and prophylactics on a rational, targeted basis. A detailed understanding of the molecular biology of virulence in a range of representative pathogens would be very valuable in understanding the strengths and weaknesses of this approach, and the extent to which there are common systems shared among organisms that might provide targets for defensive measures. The development of animal models that are appropriate for the agents of interest to the DoD—that is, models that have the same tropic factors as man—is an important objective that is not likely to be accomplished without DoD support.

Improved Classification Systems. There are a number of exciting new analytical techniques now being developed in the commercial world. The opportunity for DARPA would be to accelerate those particularly appropriate to the BWD mission—genetic analysis using planar arrays of probes, mass spectrometry, fluorescence activated cell sorting and living cell assays are certainly high-priority systems—and to encourage the type of design necessary for rugged, fieldable systems. In addition, since there is a strong reason to believe that pattern recognition may be necessary to achieve rapid identification even of known threat species. The development of a threat-specific library of characteristics is important.

Passive Protection. There are a number of components to this area. One is to establish a strong science and technology base for the production of improved vaccines (and enhanced immune responses) that could build on studies of the molecular basis for disease.

A second is the development of truly effective passive barrier protection. Most pathogens are respiratory threats, and the primary portal for entry into the body is the lungs. Masks provide good

protection against respiratory threats, but mask design has been optimized for protection against chemical weapons rather than biological weapons. The production of improved filtration materials, the enhancement of these materials by inclusion of materials such as proteases that might destroy biological agents or in situ sensors, and the development of a disposable mask suitable for rear-echelon personnel are all substantial problems in materials science. The availability of new classes of biological materials (for example, enzymes from extremophiles) may provide new capabilities in this area. Research in this area would also contribute to the development of technology for sample collection.

Sample Collection, Preparation, and Handling. The development of fieldable systems (or even high throughput laboratory systems) requires focused work in two areas: microfluidics and sample collection. Most biological analyses require manipulating small fluid samples, and microfluidics (a subject discussed in a 1995 DSRC workshop) underlies all of those advanced instrumental methodologies. Sample collection and preparation (from air, water, and soil samples) is another important and difficult problem. Fewer good ideas have been identified in this area, and fluid- (e.g. some analog of FACS) or vapor-born particulate sampling technologies need careful reanalysis for opportunities.

Technology Base. A wide range of new technologies are constantly emerging in biotechnology. Some are potentially appropriate for DoD needs: extremeophile enzymes, binding domains based on the Kunitz structural motif, ribozymes, phage display, directed evolution are examples. All of these technologies may eventually become commercial and available to the DoD, but the rate may be slow, and the direction of the technology may not be ideal for the DoD. NIH supports a particular type of biology, but this type does not necessarily overlap with the most important needs of the DoD. Active support at a low level of new technologies in biotechnology companies and in the university system could greatly accelerate the development of technologies useful to the DoD.

Systems Analysis. The problem of BWD is being approached largely as one of a collection of individual items. It would be valuable to have available a "systems analysis" of the threat: that is, to consider the entire process necessary to deter, prevent and respond to a biological attack. Technologies that are not currently at the highest level of priority (for example, decontamination) might emerge from this analysis as more vital than they are currently understood to be.

Defense Against Biological Weapons

George Whitesides

Greg Kovacs

Shawn Jones

Millie Donlon

Rose Ritts

Steve Morse

Xan Alexander

Motivation: Biological weapons are a strategic, tactical and terrorist threat to the U.S and its allies.

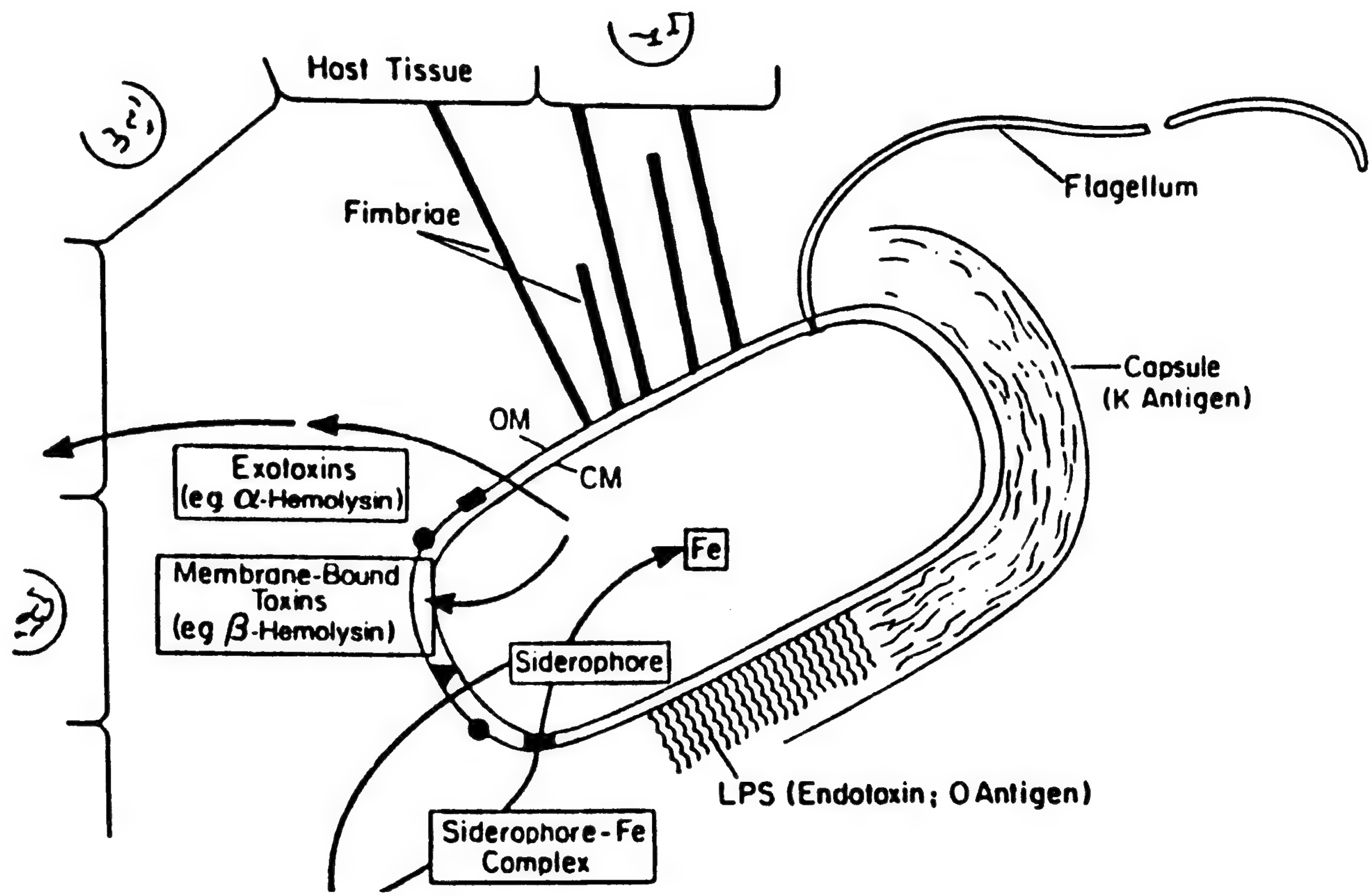
Objectives of the workshop:

To identify areas in the very complex problem of BW defense where the application of high technology will result in a large increase in capability.

Technical Survey

- **Prociv:** Overview.
- **O'Hanley:** Virulence and the molecular basis of bacterial disease in uropathogenic *E. Coli.*
- **Oldstone**: Viral disease; 300,000,000 deaths in the 20th century from smallpox.
- **Hood**: Arrays of DNA probes; ribosomal DNA for microbial strain development.
- **Smith**: Protein analysis by mass spectroscopy.
- **Sinskey**: Biochemical Engineering
- **Tananbaum**: The venture industry and biotechnology.

Molecular Basis of Bacterial Disease



Uropathogenic *E. Coli*

Efficacity of Different Strategies

	% Reduction in:	
Vaccine	Colonization	Injury
Gal,Gal Pili	*96*	*100*
Mannose Pili	*0*	*0*
Hemolysin	*0*	*90*
Necrotizing Factor	*0*	*90*

Conclusion: It is possible to attack pathogenicity based on molecular mechanisms

Information-Rich Microanalytical Systems

Emerging Technique

- DNA-based systems: especially probe arrays
- Mass spectroscopy (proteins, non-protein toxins)
- Fluorescence-actived cell sorting
- "Effect Sensors" (cell-based sensors)

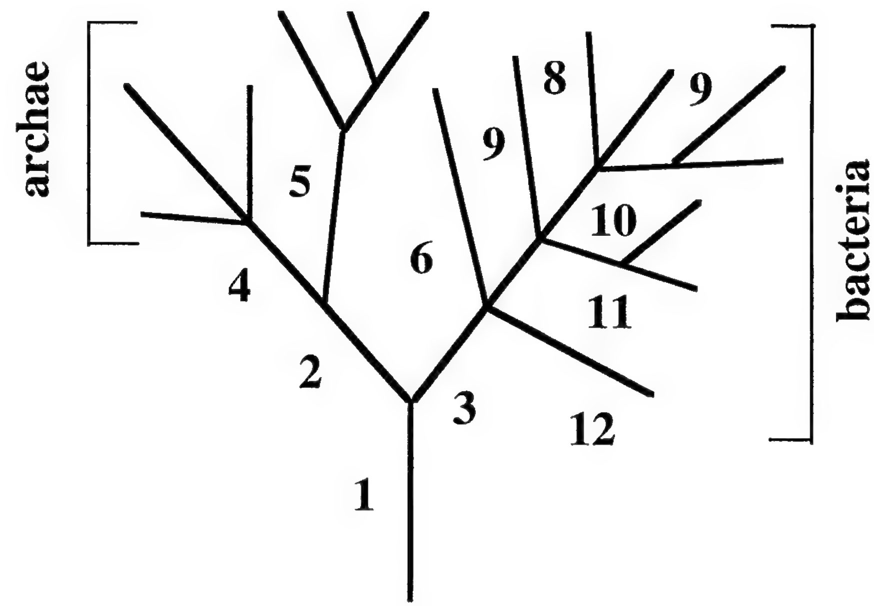
Essential, Broad-Application Technologies

- Microfluidics
- Sample collection/preparation

Complex problems require lots of data!

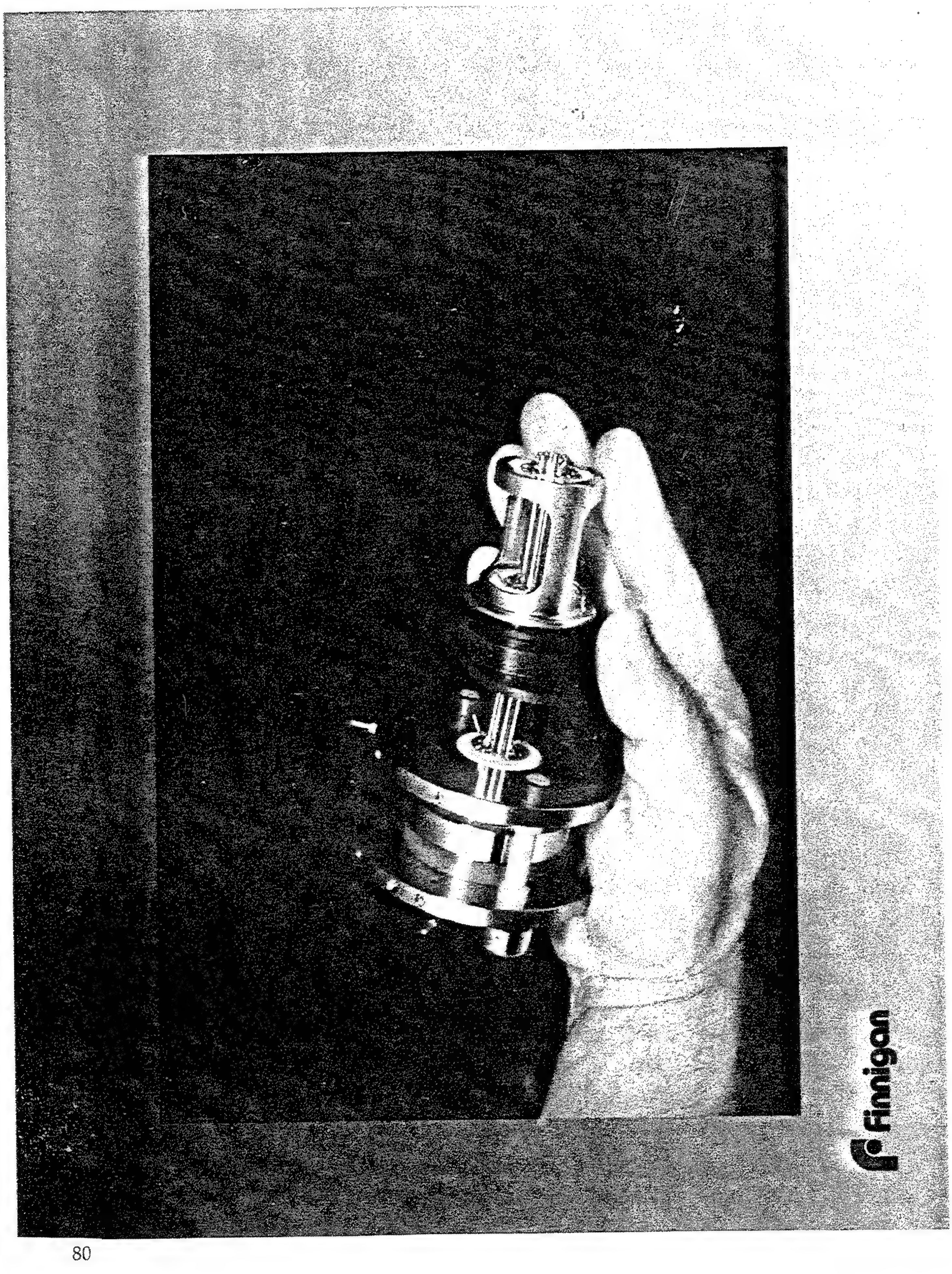
One Architecture for Bacterial Identification

- Different parts of the ribosomal RNAs are more or less highly conserved
- microbes
  - 1–10 copies of ribosomal genes
  - 10^3–10^5 ribosomes/microbe



1–12: – specific DNA probes
– 20 mers

Ribosomal Tree of Microbes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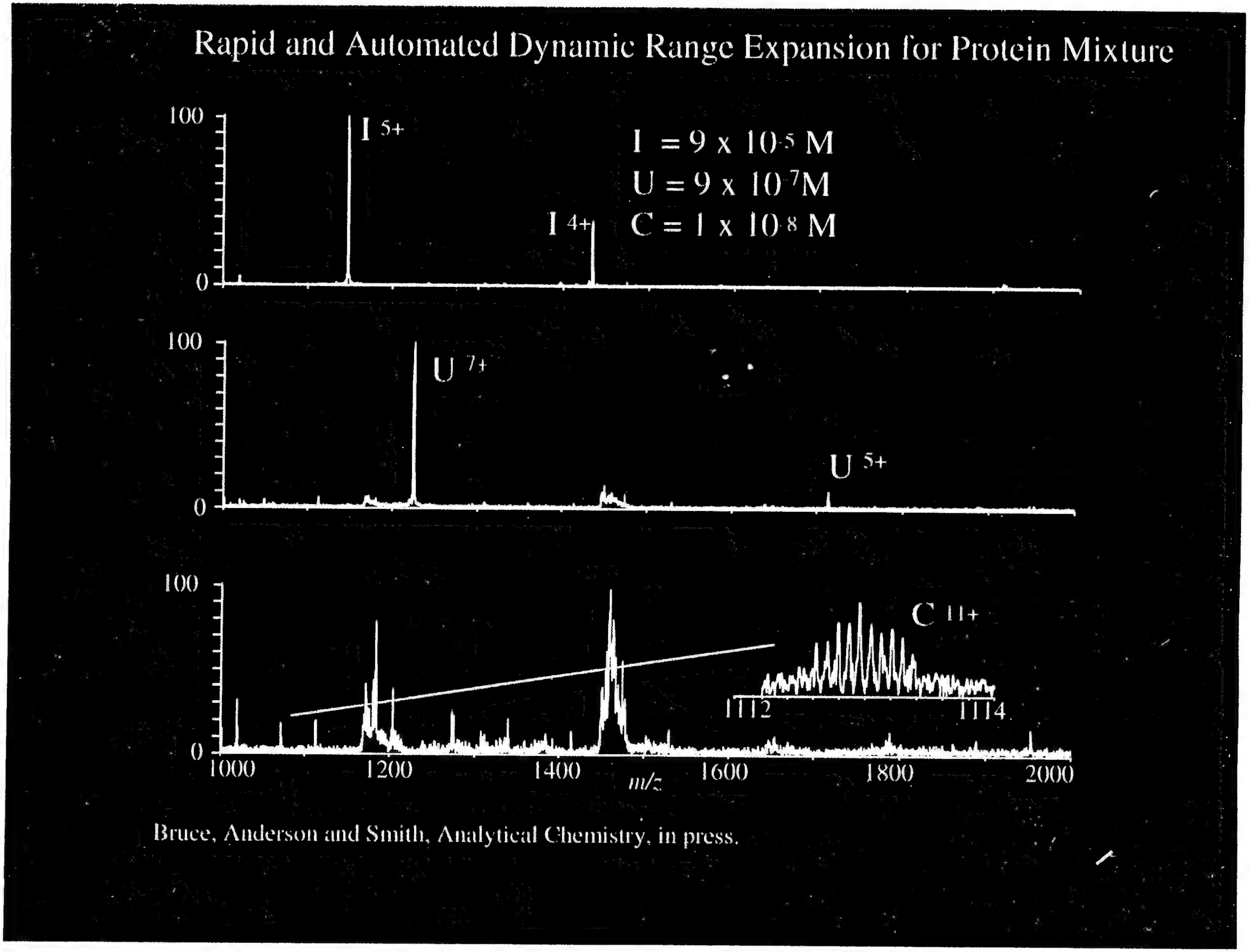
Rapid and Automated Dynamic Range Expansion for Protein Mixture
I = 9 x 10-5 M
U = 9 x 10-7M
C = 1 x 10-8 M
I 5+
I 4+
U 7+
U 5+
C 11+
100
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1112
1114
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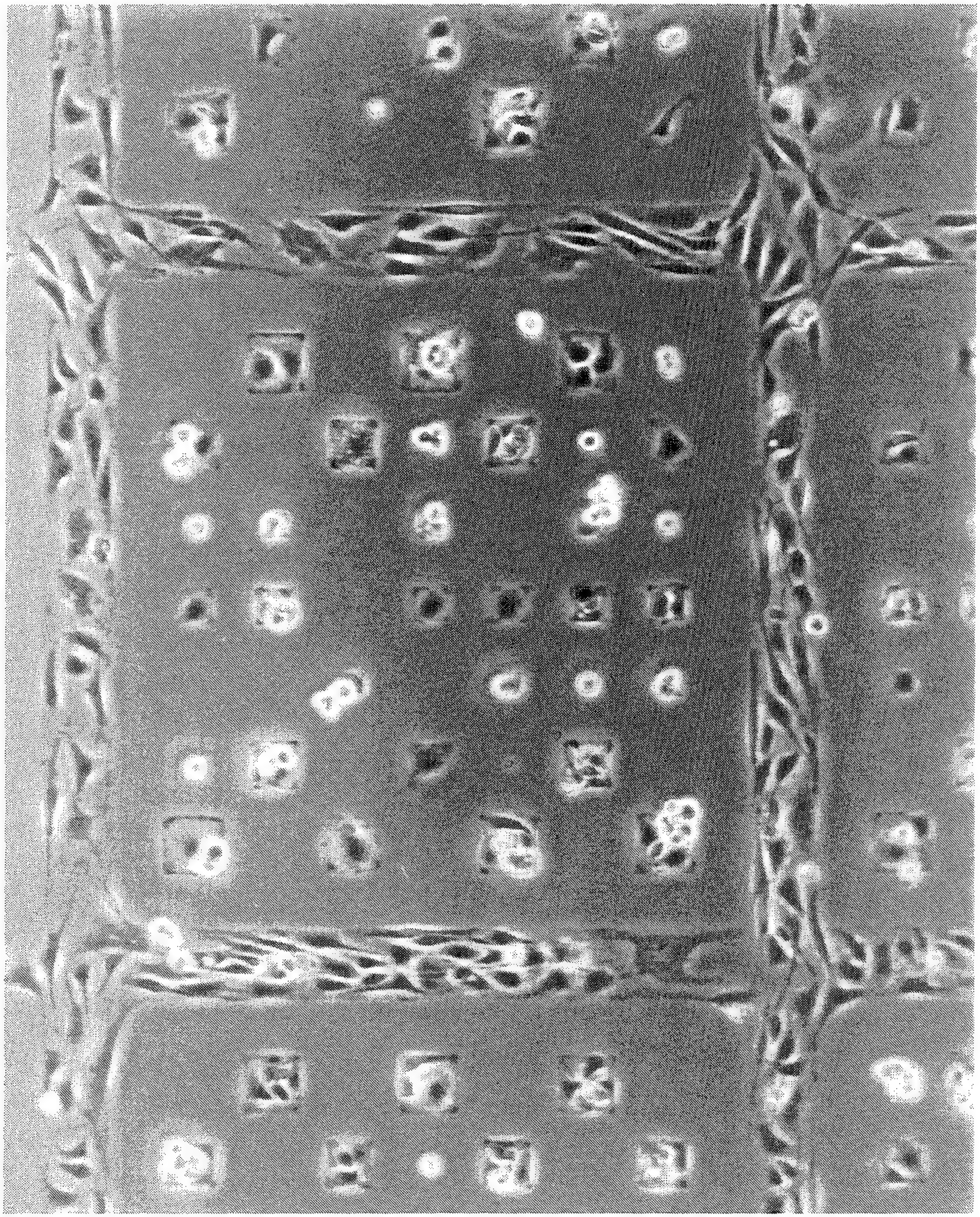
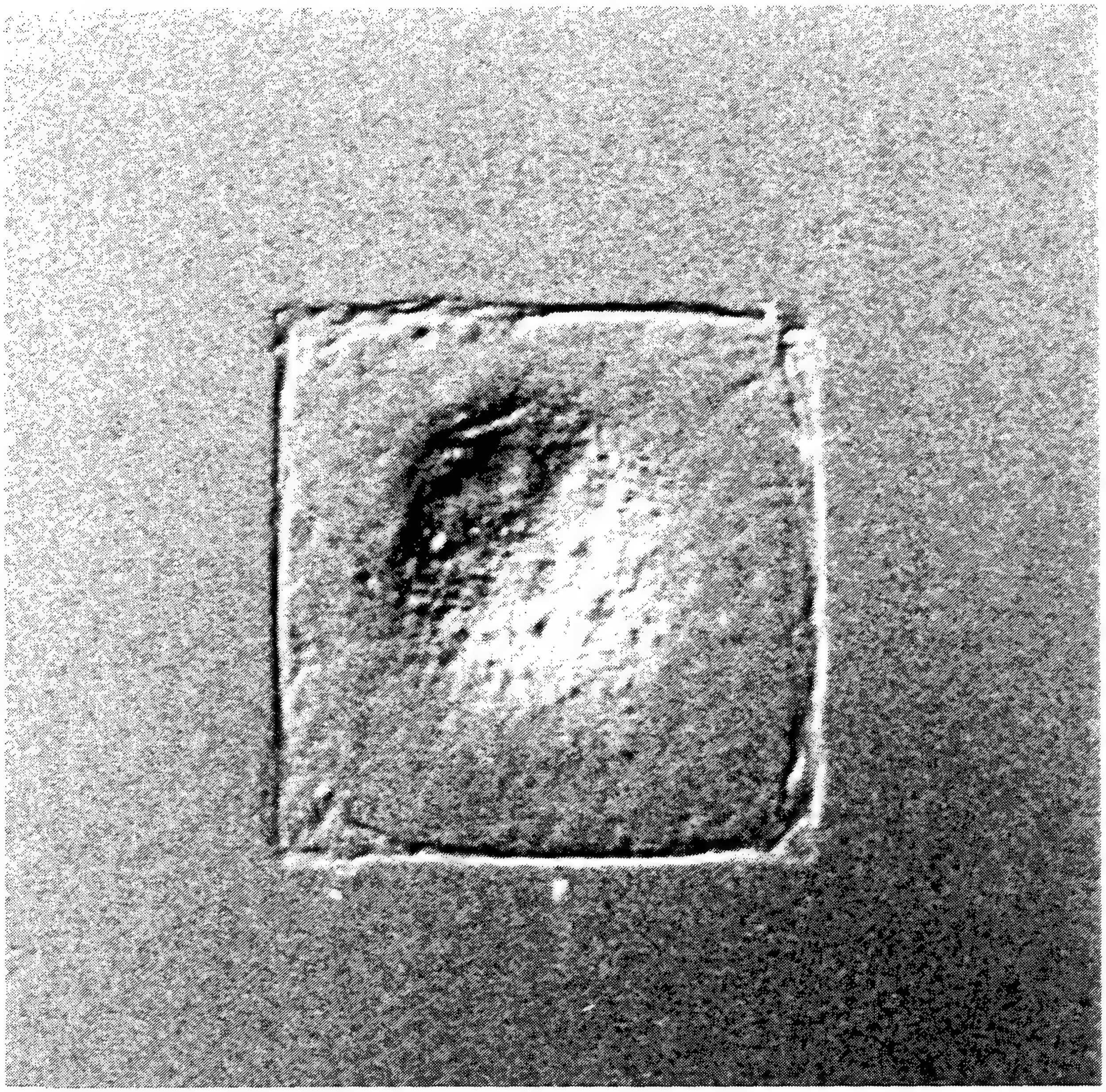
2000
m/z
Bruce, Anderson and Smith, Analytical Chemistry, in press.



Phase contrast of BCE cells in X–Y Grid of Squares (3, 5, 10, 20, 30, 40, 50 μm side length, 40 to 60 μm spacing).

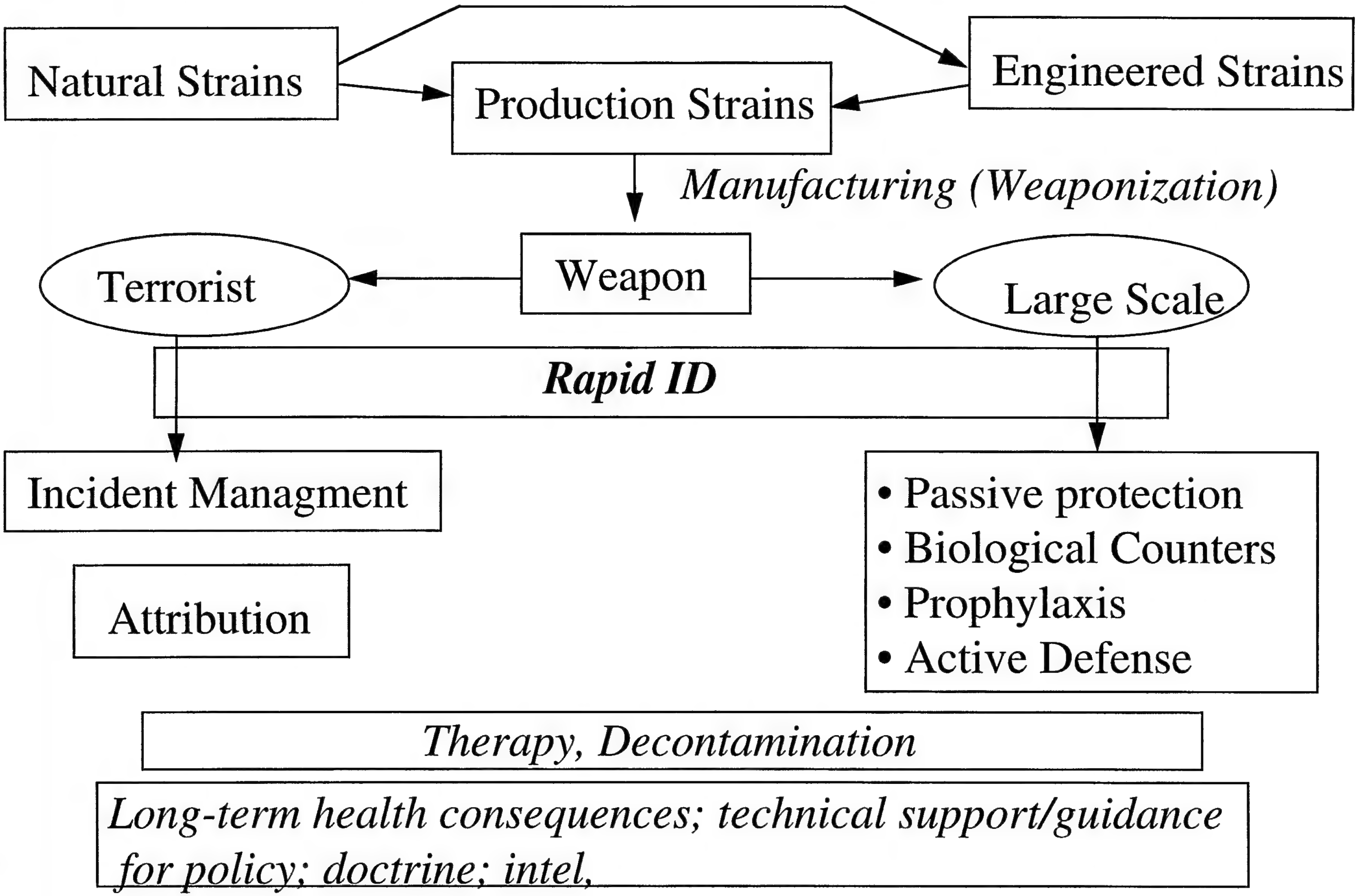


Nomarsky of BCE cell on a 40 μm square.

Other Opportunities

- Interferring with bioengineering and weaponization.
- "Passive" protection: active masks
- Technology Base: extremeophile enzymes, functional Kringle domains, phage display, other proteins
- DNA vaccines
- Systems analysis

Systems Analysis: Anthrax, Q-Fever, ...



Opportunities

- Apply, accelerate commercial/academic technology in bioanalysis: improved analytical techniques, microfluidics, sample collection/ processing, data required for identification of threats, ruggidization
- Molecular basis of pathogenicity of threats; mechanism-based treatments, prophylaxis, especially for respiratory threats; clusters of commonalities in threats and responses; animal models
- Mechanism-based vaccine design; advanced vaccine technology (e.g., DNA vaccines)
- Passive respiratory protection: “active masks”
- Advanced technology for decontamination, anti-manufacturing
- Information technology: design for expert systems for response, treatment; design of databases for threat ID.
- Systems analysis of representative threats: anthrax (bacillus), VEE (virus), Q-fever (rickettsia), botulism toxin (protein)

Advanced Technologies for Defense Against Biological Warfare Agents

Workshop Organizer: G. Whitesides

July 12, 1996

8:00 a.m.	**Introduction** George Whitesides (DSRC\Harvard))
8:15 a.m.	**The DoD Program in BW Defense** Ted Prociv (DoD Biological Warfare)
9:15 a.m.	**Break**
9:30 a.m.	**Virulence** Peter O'Hanley (Stanford University)
10:15 a.m.	**Viruses as Plagues** Mike Oldstone (Scripps Research Center)
11:00 a.m.	**Advanced Techniques for Genetic Identification** Lee Hood (Univ. of Washington)
11:45 a.m.	**Lunch**
12:15 p.m.	**Bioengineering** Tony Sinskey (M.I.T.)
1:15 p.m.	**High-Resolution Mass Spectroscopy for Protein Analysis** Dick Smith (Pacific Northwest Laboratory)
2:00 p.m.	**How the Biotechnology Industry Works** im Tananbaum (Sierra Ventures)
3:00 p.m.	**Discussion**
	Adjourn

Advanced Technologies for Defense Against Biological Warfare Agents

July 12, 1996

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LOGISTICS RESUPPLY-INDEPENDENT POWER

G. Whitesides

EXECUTIVE SUMMARY

Objective

The objective of this workshop was to survey "less-familiar" technologies applicable to production of power in military operations in which resupply of batteries and fuels was not practical.

DoD Relevance

Many military missions are limited by the availability of power. The individual soldier is increasingly dependent on power for functions from position location and communications to targeting and protection from CB threats. Sensors are a vital part of almost all military operations, and the utility and lifetimes of unattended sensors are usually limited by the availability of power. Operations of special forces may require long periods out of contact with logistics chains. In these, and in many other operations, the importance of generating power locally by appropriate processes is high.

Summary of Scientific and Technical Issues

This workshop surveyed a wide range of technologies, but also left many unexamined. It should, therefore, be considered as having sampled available technologies, rather than having covered the universe of ideas completely.

John Fielding: Harvesting Electromagnetic Radiation

Dr. Fielding estimated the availability of power from local electromagnetic radiation (AM and FM radio, TV, background EM radiation from the sun). A key finding is that the best general case was power from AM radio frequencies. With an appropriate antenna with a capture area of 10,000 square meters (the capture area is much larger than the physical size of the antenna, so an area of this size is practical), it might be possible to capture 20 mW of power. Other sources of environmental electromagnetic radiation generated nW of power over practical capture areas. The level available from AM radio (within its "service area") might be sufficient to operate a simple sensor; transmission from the sensor to an external receptor is problematic.

The practicality of stealing useful quantities of power from a stronger transmitter—for example a radar or a power transmission line—is of course much greater than from the EM background but also depends strongly on the details of the situation.

The conclusion of this presentation is that, in the absence of special circumstances, harvesting energy from random electromagnetic radiation is not practical for missions other than those requiring very low power.

Alan Bard: Solar Energy.

There is substantial power available in sunlight. (The solar flux in daylight corresponds to 350 W / square meter, and capture efficiencies are between 10 and 20%.) Conventional photovoltaic technology is progressing in an evolutionary way. There are also a number of other methods of

using solar power: one is to run a photochemical cell that generates dihydrogen or other material for use in a fuel cell; a second is to use it in the form of heat for an appropriate heat engine or pyroelectric system. All of these systems are capable of generating useful forms of power, and the development of new methods of using solar energy could provide the power needed for low-power operations.

Dave Staelin: Thermal Energy Conversion

Staelin examined one specific and one general question. The specific issue was the practicality of thermo photovoltaic (TPV) systems. In these systems, either combustion of fuel or sunlight is used to heat a metal oxide to a sufficiently high temperature (approximately 2000°C) that it becomes an intense black-body emitter, and to operate that luminous source as an emitter of radiation. The radiation from that source, coupled with an optical notch mirror, is used to excite a GaAs photovoltaic system. This system is a practical one, and in a fact a natural gas fired TPV system is now commercially available. The disadvantage of these systems is that they have about 5% overall efficiency for conversion of energy into electrical power, and the remaining 95% (as heat) thus may represent large IR signatures. These systems still also present substantial materials challenges in dealing with the high temperatures in the emitter (they have the partially compensating advantage that they have no moving parts).

The more general question addressed by Staelin was "What is theoretically the best system to use for particular power requirements and mission durations?" The answer varies, but for short intervals, conventional fuel usually wins in overall efficiency.

The best opportunities for local generation of power, in the analysis of Staelin, is to focus on small conventional engines and more robust solar and wind systems.

Thad Starner: Human-Powered Wearable Computing.

Starner examined the practicality of extracting power from human activities. The most practical system seems to be coupling heel strike to a piezo generator. An estimate of the power available by this strategy is approximately 5 W for an individual walking briskly. Other methods of extracting power from human activities—arm movement, breathing, heart, others—seem impractical for most military operations, since they require a higher level of expenditure of energy by already taxed individuals.

John Brisson: Piezopyro Polymers: A New Class of Materials for Energy Conversion?

Brisson described a system, described by others, that is claimed to couple acoustic excitation to a pyroelectric to generate power from small temperature differentials. This system is remarkable if true; it is presently premature to speculate on mechanisms and applications.

Timothy George: Small Nuclear Sources.

Small nuclear sources have been developed for the space program. These systems all involve coupling heat generated by the radioactive core into electrical energy using a pyroelectric element. This type of system might be appropriate for a very high-value unattended sensor, although the liabilities of working with radioactive materials clearly limits the utility of these systems. They do, however, provide a benchmark for very long-duration missions.

Conclusions and Observations

- **Solar.** The solar flux is sufficient to provide useful quantities of power, and sunlight is available almost everywhere. Although no new ideas emerged, consideration of photochemical generation of hydrogen to couple with a fuel cell might provide a useful source of power for a small unit. The tradeoffs between storage of power from photovoltaic cells in batteries, and storage of energy as hydrogen or some other reduced fuel, have not been examined in detail. Developing such systems could build competence in the evolving technology of solar energy generation.

- **Other solutions are local: water power is more plausible than wind power.** Other solutions for power generation are local. In regions where there is running water, a small water turbine might be useful. In the more limited regions where it might be possible to operate a wind turbine, wind power is possible. In neither area do there seem to be dramatically new ideas.

- **EM Harvesting *may* give sufficient power to operate a small unattended sensor.** The amount of power available from the background EM radiation is not large. More detailed examination is need to determine is there is enough power available (if coupled to a storage system) to run an unattended sensor using very low power electronics.

- **External interrogation and power supply should be examined.** It might be possible, in some circumstances, to use external interrogation/supply to solve the problem of the limited power available from EM harvesting. If the power could be used to run the sensor, and then to modulate the reflective characteristics of a corner cube reflector (as an example), it might be possible to interrogate the system from a UAV or an aerostat. In this situation, the power required for long-range transmission would come from an external source, not from the sensor itself.

- **Improved pyroelectric systems would have broad application.** There are a number of ways of generating heat: from sunlight, by burning locally available biomass, from small nuclear sources. More efficient methods of using heat to generate power would be broadly useful. Further, there are always small local variations in temperature: sun/shadow, day/night, surface/subsurface. Any method of capturing more of the power available in these thermal gradients would be useful.

- **Small nuclear sources are available, but obviously limited in application.** Aside from the environmental issues of a power source based on radioactive decay, the only tested method for converting the energy of decay into electrical power on a small scale now seems to be to use the heat to drive a pyroelectric system.

- **Heel-strike should be examined as a method of extracting power from human motion.** The power available from this source is limited (approximately 5 W is claimed during brisk walking, with this quantity determined by the inefficiency of piezoelectric systems). What is unclear is whether extracting this energy makes sense in terms of its influence on the weight of the boot and attendant systems, and the change in the "feel" of walking when energy is being extracted.

Logistics Resupply-Independent Power

George Whitesides

Motivation: The availability of power limits many DoD applications. New sources of power—independent of resupply—are needed.

Objective of the Workshop: To survey "less explored" sources of energy—from solar to nuclear—for opportunities.

- Available from the environment
- High power density
- Portable, reliable

Technical Survey

- Solar: H2-producing solar cells (for coupling to fuel cells); photovoltaics; heat.
- Thermal: solar and fuel-based thermal photovolatics (TPVs)
- Electromagnetic Field Harvesting; radio, TV, EM background
- Nuclear

Power (all or part) supplied externally: e.g., laser plus transducing, reflecting corner cube.

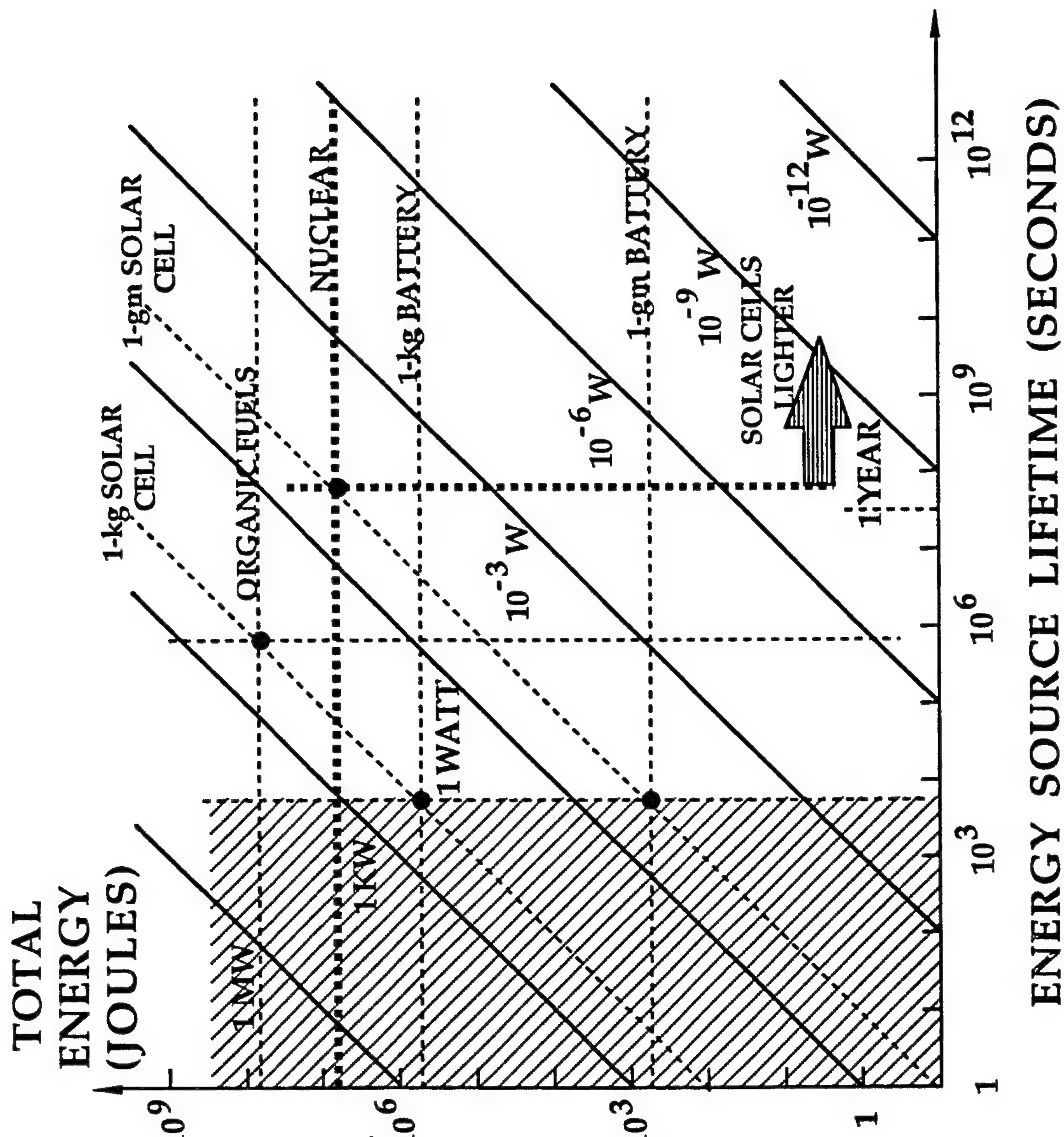
ENERGY STORAGE CHARACTERISTICS

	kWH/kg	kW/kg	ROUND-TRIP EFFICIENCY
SUPERCAPACITOR	~ 0.001	~ 1	~ 0.8
FLYWHEEL AND MOTOR	~ 0.015	~ 1	~ 0.85
CHEMICAL BATTERIES	0.02-0.2	0.02-0.2	~ 0.7
EXOTICS	0.2-0.5	0.2-0.5	
FUELS	~		
H_2 IN M_G HYDRIDE	0.7		
METHANOL	6		
DIESEL	13		
GASOLINE	14		
METHANE	16		
NUCLEAR	> 1000		

DHS (7/15/96)

EM ENERGY GLEANING

SERVICE	FIELD STR V/M	PWR DEN W/SQ M	WAVELEN M	CAP AREA SQ M	POWER W @ (10%)
AM RADIO	10**-2 10**-4	2.7x10**-7 2.7x10**-11	300	10**4	2.7x10**-4 2.7x10**-8
FM RADIO	3.16x10**-3 10**-3	2.7x10**-8	3	1	2.7x10**-9
TV (2-6)	5x10**-3	6.6x10**-8	5	3.3	2.2x10**-8
TV (7-13)	7x10**-3	1.3x10**-7	1.5	0.3	4x10**-9
TV (14-69)	10**-2	2.7x10**-7	0.5	0.033	9x10**-10
ATM NOISE	3x10**-5	2.4x10**-12	15-30		
RAD SAFE		10			
RAD HAZD		100			
SOLAR		1000			


TOTAL ENERGY (JOULES)
ENERGY SOURCE LIFETIME (SECONDS)
1 MW
1 KW
1 WATT
10^{-3} W
10^{-6} W
10^{-9} W
10^{-12} W
1-kg SOLAR CELL
1-gm SOLAR CELL
ORGANIC FUELS
NUCLEAR
1-kg BATTERY
1-gm BATTERY
SOLAR CELLS LIGHTER
1 YEAR
1
10^3
10^6
10^9
10^{12}

Conclusions

- Solar the best bet
- There are alternatives to direct photovoltaics: thermal photovoltaics, production of H_2 or other fuels
- No other environmental harvesting solutions have broad application: ΔT, wind, water, concentration gradients, …
- EM harvesting may be enough to run a simple sensor (ca. 10 mW/10^4 m^2); power for transmission from a sensor is difficult
- External interrogation possible (laser and corner cube reflector)
- Water > wind as power sources, but both possible in appropriate environments
- Heel strike (with piezoelectrics) is the only plausible power source from human motion.
- Small nuclear power sources are technically feasible
- A variety of solutions needed

Energy from the Environment

Workshop Organizer: G. Whitesides

July 15, 1996

8:00 a.m.	**Introduction** George Whitesides (DSRC/Harvard)
8:15 a.m.	**Harvesting Electromagnetic Radiation** John Fielding
9:15 a.m.	**Break**
9:30 a.m.	**Solar Energy** Alan Bard (University of Texas-Austin)
10:15 a.m.	**Thermal Energy Conversion** Dave Staelin (Massachusetts Institute of Technology)
11:00 a.m.	**Human-Powered Wearable Computing** Thad Starner (Massachusetts Institute of Technology)
11:45 a.m.	**Lunch**
12:15 p.m.	**Piezopyro Polymers: A New Class of Materials for Energy Conversion?** John Brisson (Massachusetts Institute of Technology)
1:15 p.m.	**Small Nuclear Sources** Timothy George (Los Alamos National Laboratory)
2:00 p.m.	**Discussion**
	Adjourn

Energy from the Environment

July 15, 1996

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MESOSCOPIC MACHINES

G. Kovacs

EXECUTIVE SUMMARY

Objective

The objective of this workshop was to explore the size domain between MEMS (microelectromechanical systems) and conventional-scale machines. An important aspect of this exploration was to consider scaling laws and their importance to a wide variety of machines and devices in this size range. A key objective of this effort was to ascertain whether or not there are unique properties and/or advantages to such devices and systems.

DoD Relevance

Many opportunities exist to realize improved or previously unavailable functions with in the mesoscopic, or "sugar-cube-to-fist-sized" domain. The domains in which mesoscopic machines could have tremendous impact include refrigeration/heating, energy conversion/generation, miniature chemical reactors for point-of-use generation/destruction of compounds (including active BW/CW masks to replace current charcoal filters), propulsion systems for autonomous mobile structures (e.g. mine detection/neutralization robots) and for larger vehicles, air samplers for detection of chemical/biological warfare agents or explosives, general mechanical functions, etc. Developing mesoscopic machines may provide considerable improvements over existing solutions or provide wholly new ones.

Summary of Scientific and Technical Issues

Ted Nast (Lockheed Martin): Mini Cryocoolers

Dr. Nast provided an overview of current "miniature" cryocooler technology. The basic idea is to use a compressor to generate oscillatory pressure waves in a gas (typically helium at 10–15 atm) that are conveyed to a displacer where expansion cooling occurs. Extremely long lifetimes are currently achievable through the use of linear (voice-coil) actuators (without gearing or other rotating components) and thin, chemically-etched BeCu or steel flexures run below their infinite fatigue limits. Precision machining allows for the use of clearance seals rather than bearings or gaskets. Using these approaches, efficiencies of 40–60%, weights as low as 400 g, volumes as low as 300 cm^3, 2–5000 hour operating lifetimes and power consumptions of 6–17 W have been achieved. Another approach to mesoscopic refrigeration technologies is the orifice pulse tube, capable of providing cooling down to 60 K in a single stage, while eliminating the moving parts associated with the expanders of typical Stirling cycle devices (in the pulse tube, a column of gas acts as the expander thanks to a carefully controlled phase relationship to the compressor). Reliability is enhanced and performance on the order of 1 W power for cooling to 80 K with a 38% efficiency can be achieved.

Scaling down such coolers too far is apparently not beneficial. Larger coolers are generally more efficient due to smaller surface area to volume ratios (and hence reduced losses), as well as lower frictional, pressure drop and conduction losses. However, there are apparently no "show-stoppers" in scaling to smaller sizes, but required cooling loads will have to be scaled down (0.1–10 mW

range for 77 K) and operating frequencies scaled up. Dr. Nast felt that one of the rate limiting steps in scaling and optimization is better modeling software. At present, extensive models exist, but only agree with actual systems on the order of 50%.

<u>Jerry Martin (Creare, Inc.): Miniature Fluid Machines for Vacuum and Refrigeration</u>

Dr. Martin gave an overview of fluidic devices in the mesoscopic size domain. He felt that 25 µm to 2.5 mm size features (e.g. flow channel diameters), with flow rates in the 0.25–250 ml/s range roughly defined mesoscopic fluidic devices. He described many possible applications of mesoscopic fluidics including heat exchangers as recuperators/regenerators for cryocoolers, electronics cooling and capillary pumped systems. Many types of turbomachines, including reverse Brayton cycle systems, miniature vacuum systems (e.g. roughing pumps for portable mass spectrometers), implantable drug pumps, etc., were also mentioned as likely application areas.

He described several examples of mesoscopic machines, including a reverse Brayton cycle cooler comprising a turbocompressor, turboexpander and heat exchanger, all on the mesoscopic scale. This device can provide a few Watts of cooling power at 35–65 K, and was fabricated using custom electric discharge machining (EDM) methods. The turbines used reach tip speeds of 300 m/s at rotational rates of up to 600,000 rpm while retaining micron clearances between turbine blades and sidewalls. Critical to the success of this device is the use of gas bearing technology to attain the high speeds required. In contrast to the rotating turbomachines, Dr. Martin also described a mesoscopic peristaltic pump using an array of piezoelectric stack actuators to achieve pumping rates from 0.05–0.15 ml/s. This pump is being developed for use as a roughing pump for a miniature mass spectrometer.

The key fabrication technology Dr. Martin described was EDM technology that provides extreme precision (10 microns accuracy and 2.5 µm repeatability). While the fabrication times may be long due to their serial nature (in the 25–250 hour range for the fabrication of a single impeller), the high precision and fully three-dimensional components possible often outweighs this factor. He also pointed out that electroforming and precision stamping are extremely useful alternative techniques for fabricating mesoscopic machines.

Dr. Martin stated that a large number of portable equipment items (1–100 W power levels) are being driven to the mesoscopic size range. A key reason for this is that there are significant benefits to this size range, particularly in the heat-exchange area. Returning to the example of miniaturized mass spectrometers, he made the general point that in many cases, the miniaturization of sensors has greatly outstripped the miniaturization of the supporting devices (e.g. pumps).

<u>Bob Wegeng and Kevin Drost (Pacific Northwest National Laboratory): Energy and Chemical Systems Miniaturization</u>

Drs. Wegeng and Drost jointly presented an overview of mesoscopic fluidic devices for heating/cooling, point-of-use power generation, chemical generation/destruction, etc. It was pointed out that at this scale, high heat transfer rates and short residence times can be readily achieved, and that great reductions in size and weight can be achieved for systems where the currently large, centralized machines are replaced by a number of smaller, distributed, mesoscopic counterparts.

For heat transport, the relatively high surface-area-to-volume ratios possible make very high convective heat transfer coefficients possible (at 1–2 psi pressure drops, 13–15 kW/m^{2}K for non-boiling flow and 20–30 kW/m^{2}K for boiling flow, neither apparently near the possible limits). While some of the assumptions might not be met in practice (i.e. fully developed laminar flow), the basic idea presented was to reduce channels lengths as flow channel widths are narrowed, partly

compensating for the pressure drop induced by the smaller channels. Absorption cycle heat pumps were described that could lead to 10X reductions in size versus conventional heat pumps, and operate favorably in any orientation. Combustors were also discussed, including a mesoscopic design that has been shown to have 85–93% efficiency, a rapid start-up time (1 minute) and 30 W/cm^2 heat transfer rate.

In terms of chemical systems, Dr. Wegeng pointed out that there is a host of chemical processes that are more efficient at a small scale, where large surface areas and short residence times contribute to high performance. One example presented was a microchannel plasma reactor for destruction of chemical and biological weapons. The mesoscopic size scale avoids problems with further miniaturization (shorting of high voltage across plasma channels and elsewhere) and provides high performance through several mechanisms. One is the lower operating voltages required due to the short conduction pathways and defect-free dielectrics possible. Another is that the relatively high energy density in the small volumes leads to high quality plasmas. Prototype mesoscopic plasma reactors have demonstrated equivalent throughput to devices 1000 times larger and using one quarter the energy.

In another chemical system example that combines advantages in heat and mass transport, a catalytic partial oxidation reactor to produce "syngas" (hydrogen and carbon monoxide) by partially oxidizing methane. The conventional approach to this is to use steam reforming, requiring large amounts of external energy, large reactors and long residence times, making it impractical on a small scale. An alternative approach, large-scale catalytic partial oxidation, is highly exothermic and thus difficult to control. Scaling the catalytic approach to the mesoscopic domain allows this to be overcome due to greatly improved transport properties. It was estimated that a one cubic meter mesoscopic reactor of this type could supply more than one million cubic feet of hydrogen per day. This approach was extended to the more general case, wherein a multistep mesoscopic fuel processor could be integrated in vehicles to allow local conversion of a variety of fuels (e.g. methanol) to hydrogen for fuel cells.

Several examples of future mesoscopic systems were presented, including distributed power and HVAC systems for large ships, devices for person-portable combat applications (air decontamination, power generation and microclimate control). A potential future point-of-use thermal power generation scheme that was presented as a target for future research was a liquid metal heat engine. Liquid metal (e.g. Ga/In/Sn) flows between two permanent magnet poles would be used to generate electrical power (picked up using two electrodes, orthogonal to the magnetic poles). Point-of-use generation of potentially harmful chemicals (e.g. cyclohexyl isocyanate, methyl isocyanate, hydrogen cyanide and phosgene) was discussed, since operating the necessary reactors in the mesoscopic size range can greatly increase the controllability of the reactions as well as reduce the quantities on hand in the event of an unintentional release. Another future chemical application discussed was the insertion of mesoscopic chemical reactors directly into toxic waste tanks or spills to carry out *in-situ* remediation.

Klavs Jensen (MIT): Microchemical Systems for Chemical Production

Prof. Jensen provided an overview of mesoscopic chemical systems, along with the motivation for their development. Key drivers for mesoscopic chemical systems include: higher reactor productivity, higher product selectivity over competing reactions, low site capacity for safety, continuous production, the ability to address reactions that are not amenable to larger systems (e.g. thin-film catalysis, inorganic membrane reactions, photochemical reactions), rapid development of new

products, and capabilities for rapid variations in production rates. Most work today is focused on fabricating or reacting hazardous materials in small batches (examples include: cyclohexyl isocyanate, phosgene, methyl isocyanate, hydrogen cyanide, etc.).

He presented partial oxidation reactions as candidates for mesoscopic operation since they are rapid and difficult to control (i.e. proceed all the way to CO^2 and water). In large-scale systems, small changes in feed temperature or concentration can lead to thermal runaway and explosions. These reactions are limited by heat transfer and are run conservatively by diluting the oxygen with something inert (e.g. N^2), leading to large separation costs. The large surface-area-to-volume ratios of mesoscopic reactors provide for safer operation with higher conversion efficiency and selectivity.

He described a lithographically-fabricated "chip" reactor they are developing in cooperation with DuPont. This devices uses a 0.5 μm silicon nitride membrane with on-board heaters, catalyst regions and thermal anemometers to control an ammonia oxidation process. The reaction ignites at 180°C and jumps to 300°C, making it difficult to shut down on a macroscopic scale. At the miniaturized scale, the system is quite controllable, but still subject to some of the problems that affect larger ones, such as fouling, catalyst deactivation, etc.. Simulation of such systems is critical to predict flows, temperatures, chemical species profiles and to facilitate comparison to macroscopic reactors. His suggested approach is to use finite element methods to solve fluid flow, energy and chemical equations (both gas and surface state).

Key comments had to do with scaleup to parallel mesoscopic systems with throughputs equivalent to macroscopic reactors. The idea is to use local controls to allow for the parallelism with relatively simple building blocks. Most of the effort will have to be dedicated to interconnection design (electrical, thermal and flow distribution). Technical challenges include not only these interconnect issues, but also developing concepts for analyzing mesoscopic reactors, controlling particulates, avoiding the formation of solid reaction products, and development of novel catalysts required (conventional catalyst pellets cannot be employed). By addressing these issues and developing design tools for such massively parallel systems, entirely new chemical reactor concepts will be enabled.

Fritz Prinz (Stanford): Scaling and Fabrication of Mesoscopic Machines

Prof. Prinz provided a generalized discussion of fabrication and scaling of mesoscopic machines, rather than discussing specific devices. He began with a discussion of size scaling laws, pointing out that the following properties are scale independent: speed and energy density. One can theoretically show that for a hypothetical large machine of volume n^3 (i.e. an n-by-n-by-n assembly of smaller cubes of unit volume), an assembly of n^2 unit volume cubes could deliver the same power output if the operating frequency was scaled up. In practice, this does not work so well, due to several issues. Wear life scales as L^2 (dropping dramatically at small scales), fluid friction scales as L^{-1} (increasing with smaller scale), warpage due to long range internal stresses scales as L, it is more difficult to maintain tight tolerances with smaller machines (especially over temperature) and conventional combustion processes do not scale well below 1 mm. In addition, several issues limit the implementation of such systems, including fuel delivery, cooling, power lines, control lines and the need for air bearings. It is important to note that the bulk of these issues are interconnect problems.

Prof. Prinz stated that, in many cases, to produce massively parallel, mesoscopic machines, free-form fabrication, with direct links to three-dimensional CAD tools will be necessary. He contrasted this approach to the traditional "shape first/assemble later" approach wherein components are fabricated separately and then assembled later. Free-form fabrication allows them to be fabricated

in parallel and can eliminate the assembly step. He noted that solid free-form fabrication (SFF) is still relatively immature, but has important advantages over traditional methods: additive and subtractive processing in combination, ability to mix different materials at will within a single structure, ability to embed separately fabricated structures/devices, etc. SFF is one way to fill the gap between microlithographic fabrication (i.e. MEMS) and conventional machining. Current limitations of SFF include difficulty in handling and fixturing the small parts that can be realized, limitations to spatial tolerances, difficulties controlling the microstructure of the resulting materials, production rate and cost.

Steve Hotelling (Gyration, Inc.): Fabrication Strategies for Mesoscopic Inertial Machines

Mr. Hotelling discussed strategies for the design and fabrication of mesoscopic inertial machines, in particular multi-axis gyroscopes for medium-precision applications (pointing devices, as opposed to inertial-only navigation, for example). He presented case studies of their implementations of both rotating ("spin") and vibrating gyroscopes.

Their spin gyro design makes use of precision injection molded components, ultrasonically welded together and immersed in a perfluoro polyetherimide fluid (low viscosity). With integral printed-circuit-board-hybrid electronics, the system uses 100 mW to operate at a 8,000 RPM spin speed. Their resonant gyro was designed to overcome limitations of the spin design as well as those of conventional resonant devices (such as those employed for camcorder stabilization). The most important limitations of those devices are noise and drift (<1 degree/s needed for pointing applications).

In order to address these issues, a tuning fork type resonant gyro was fabricated using technologies of the disk drive and watch industries. Thermally stable FeNi alloy sheets are used to form the resonant beams, cold rolled, fine blanked in critical areas to tolerances of ± 12 microns and batch lapped to ± 5 microns. By avoiding designs that require matching the frequency of the drive and sense mode frequencies of the gyro (in fact choosing one with the two frequencies deliberately detuned), it is possible to achieve low, but exquisitely stable sense amplitudes independent of mechanical Q-factors. NdFeB magnets are bonded onto the tuning fork beams, which are in turn resistance welded to mounting plates and a single contact point is made to the tuning fork to avoid thermal mismatch problems. Electromagnetic excitation coils, fabricated by conventional winding (much better performance than lithographic methods at this scale), are bonded into injection molded carriers that are in turn aligned and bonded to the overall assembly. A conventional printed-circuit board, complete with the custom gyro ASIC is then added to complete the assembly, and connected using a conventional wire harness (flex circuits proved to offer poorer performance at greater cost). The completed gyros offer 11 mW power consumption, meet drift specifications, can survive 1000 g shocks, and have approximately 1 mV/degree/s sensitivity at a cost of < $10 axis.

A key observation of the economics of fabricating such devices at the mesoscopic scale is that an optimized system design may, in some cases, reach a cost minimum only within that size range. In this case, scaling up will increase raw materials costs dramatically, while scaling down will require denser electronics and higher component tolerances.

Alan Epstein (MIT): Mini Jet Engines

Prof. Epstein gave an overview of the large, multidisciplinary program at MIT to develop micro gas turbine engines and generators on the low end of the mesoscopic scale (1cm diameter, 1 mm thick... "the size of a shirt button"). Primarily for power generation, this approach was chosen due to its reduced complexity compared to alternative engines. Other motivations for the work are: power densities for the mesoscopic turbines could approach those of their macroscopic counterparts

(100W/cm^3), cost could be reduced greatly given sufficient demand, environmentally friendly power generation and propulsion would be possible, distributed propulsion for vehicles would be enabled, etc. While the long-term goals are to fabricate these devices using refractory ceramics, the necessary components (bearings, generator, combustor, turbine, compressor) will be demonstrated in silicon using micromachining technology (for a system goal of 300°C operation at eight atmospheres pressure, compared to the ultimate goal of 900–1400°C for the ceramic versions).

Key scaling effects for the mesoscopic implementations of jet engines include the increased surface-area-to-volume ratios, the increased importance of viscous effects, shorter time scales (higher rotation rates) and generally improved materials properties at this scale. Due to the necessity to use lithographic ("MEMS") fabrication methods for the prototypes, the designs are necessarily constrained to two-dimensional extrusion shapes, leading to the realization that optimal system and component designs may be quite different. A key constraint is to devise a design that meets the required performance specifications while meeting the constraints of realizable fabrication technology. In parallel to the MEMS-type prototype fabrication (with relatively long turnaround time for modifications), macro-scale models are being developed that are much easier to fully instrument.

Prof. Epstein discussed the issues leading to the baseline design with a total weight of 1 g, an inlet area of 1 mm^2, an airflow of 0.2 g/s, a pressure ratio of 4.5:1, an inlet temperature of 1600 K, a thrust/power of 0.2 Nt/10–20 W, and a hydrogen fuel consumption of 8 g/hr. The plan is to migrate over time to a higher performance, JP-8 fueled version with up to 100 W/g power densities. These predicted power-to-weight figures are much better than, for example, typical automotive or helicopter engines. More importantly, due to the much higher specific energy of hydrocarbon fuels (10–12 kW hr/kg for 3.5 kW hr/kg typical net specific energy versus 175 W hr/kg), the net energy density is on the order of fifteen times greater than the standard military $LiSO_2$ batteries (3000 kW hr/m^3 versus 200 kW hr/m^3).

Key research tasks include establishing material properties (and hence design space), the development of stress relief structures that can be realized through micromachining, modeling of thermal/mechanical/fluidic parameters, etc. An electrical generator will need to be developed that can operate at 3 X 106 rpm. Another key element required for successful system demonstration is the development of air bearings that can operate at the extreme speeds required. In addition, efficient switching circuitry will be required at hundreds of volts to handle the power generated. Finally, all system components will have to be integrated together. System integration issues include overall packaging and auxiliary systems (start-up, fuel delivery, control), etc.

An important paradigm shift that would occur with such mesoscopic systems is that the overall weight would now be dominated by fuel, rather than hardware. This would have broad impact across a variety of DoD applications requiring electrical power or propulsion.

Robert Full (U.C. Berkeley): Animal Locomotion/Biological Inspiration for Micro Robots

Prof. Full gave an overview of animal locomotion at the mesoscopic scale, with the goal of drawing inspiration from this for the design of mesoscopic mobile platforms (of which few exist at present). He began by pointing out that the vast majority of animals on the Earth are mesoscopic, and that at these scales, inertia and gravity, as well as viscous forces, are important. Such animals (2, 4, 6, 8 or more legged) make use of dynamic effects, moving like inverted pendulums or spring-mass systems, depending upon speed. At low speeds (i.e. walking), inverted pendulum motion is used, at a 50–70% energy savings compared to running, when spring-mass dynamics dominate. At a

species-specific speed, there is a transition from "trot to gallop," up to a maximum sustainable stride frequency that scales with animal size (after that, speed is increased by taking longer strides). Few, if any, robots in existence can operate by switching modes in this manner.

A key lesson learned from studying a broad range of animals is that mesoscopic animals can fly, run and swim at speeds practically equal to larger animals. Thus, it can be seen that speed is not directly proportional to size, and does not decrease as mass decreases. However, the relative speed (relative to body length) does scale, and mesoscopic animals travel at nearly unimaginable speeds, mostly attained through high cycling frequencies (increasing greatly in small animals, as high as 1000 Hz for the mosquito).

A particular disadvantage of mesoscopic animals is their low locomotion efficiency. Smaller animals require more energy to move a unit of mass than larger animals, leading to metabolic efficiencies (mechanical energy output/metabolic energy input) of less than 1% (far lower than for larger animals). However, a tremendous advantage they possess is a greatly increased strength-to-body-mass ratio. Volume scales as length cubed, while area scales as length squared, so a small animal has a much greater relative amount of surface area. This can translate into greater force, allowing mesoscopic animals to carry very heavy (relative) loads (many insects can carry 10–100 X their body weight), bite hard, and jump nearly as high as larger animals. Their high force-to-weight ratios also allow them to "walk up walls" an even move themselves along upside-down. They can survive large falls since drag is also dependent on surface area. The power-to-mass ratio is also very high at the mesoscopic scale.

Considering the importance of viscous forces at mesoscopic (and smaller) scales, it is possible for some animals such as water striders, some beetles and even Basilisk lizards to literally "walk on water." For this to occur, viscous forces must exceed muscle forces. As they are scaled below the mesoscopic range, sticking forces dominate, and if they are scaled larger, support forces increase, making it impossible to be supported by water surface tension. In addition, at the mesoscopic and smaller scales in liquids, the velocity of limb movement can make the difference between locomotion and sieving action. For example, copepods, small aquatic crustaceans, operate their limbs slowly (low Reynolds number) for paddles (locomotion) or fast (higher Reynolds number) for raking or sieving food.

He pointed out that the relative individual leg stiffness (important to spring-mass dynamics) is nearly identical in diverse animal species. The key message in this appears to be that simple mechanical principles and designs work for running across huge differences in morphology. For high static stability (in wind or currents), sprawled posture and increased number of legs is key. Differential leg design with overlapping work-spaces and minimized joint movements give optimum stability and maneuverability. Behavior-based, decentralized control is very effective, particularly when coupled to tuned systems capable of passive, dynamic adjustments. The best way to take advantage of this information is to apply it to the design of robots in the mesoscopic scale. Not all animal locomotion strategies should necessarily be directly mimicked (i.e. beating wings for flight), but many useful lessons can be learned.

Conclusions and Observations

Microelectromechanical systems, or MEMS, are making increasing contributions to military systems. Due to the use of integrated circuit fabrication techniques to realize them, their sizes can range down to the truly microscopic and, in practice, up to perhaps one centimeter for a maximum dimension. This tremendous scaling down from conventional machines often confers advantages in terms of mass, volume, power and performance. If silicon forms part of the devices, circuits can

be integrated. However, all scaling laws do not lead to optimal performance on this greatly reduced scale. In addition, the use of integrated circuit type lithographic methods yields structures that are, for the most part, two dimensional.

In contrast, "conventional" machines are fabricated using traditional mechanical methods, including the use of end mills, drills, lathes; stamping; casting; forging, etc. In addition, some newer fabrication techniques such as free-form/laminated object manufacturing have greatly increased the capabilities to fabricate complex structures. These fabrication methods, while generally not as parallel as those used for MEMS, offer truly three dimensional fabrication capabilities in a practical fashion.

Mesoscopic machines straddle not only the sizes of MEMS and conventional machines, but also the fabrication techniques. Mesoscopic systems may include (or even consist of) MEMS components, or may be fabricated using a combination of non-lithographic methods. By applying the best of MEMS and "conventional" machine fabrication techniques to the mesoscopic domain, useful new devices and systems can be realized.

There are several important properties that arise in mesoscopic systems for thermal, chemical, and mechanical applications. Key advantages of mesoscopic thermal and chemical devices are due to the enhanced heat, mass, momentum and electron transport properties of structures on this size scale. For a wide variety of chemical reactions and fluidic functions, the optimal size range is mesoscopic. If one makes a system larger, it becomes difficult to control heat and fluid flows, while shrinking the system too much leads to dominance of thermal and fluidic properties by wall interactions. For mechanical devices, scaling laws can potentially be taken advantage of to replace large machines with many, smaller machines for equivalent power with greater system reliability. In addition, materials properties do not change significantly at these dimensions, often leading to better performance as strains, pressures, etc., are scaled. Moving into the mesoscopic range can sometimes minimize mass, power and materials costs while maintaining performance of larger systems (e.g. through parallel arrays of smaller devices). In addition, the mesoscopic machines can take advantage of the best of MEMS and conventional fabrication techniques.

There are several areas within the category of mesoscopic machines that are likely to yield significant results:

Mesoscopic chemical reactors. Chemical reactors in this size range offer tremendous advantages over their macroscopic counterparts. Particular advantages include: increased controllability and safety for certain reactions, increased product selectivity, low site capacity for safety, flexibility, capability to make portable reactors for point-of-use synthesis/destruction of chemicals, the availability of reactions that are not feasible at larger scales, and massive parallelism for reliability and high throughput. Mesoscopic reactors could be paralleled to generate equivalent throughput to larger reactors while maintaining many of the benefits outlined above. Important research issues include interconnection issues (important for parallelism), thermal and mass transport at the micro and molecular scales, packaging and modeling tools. DoD applications could include chemical/biological warfare agent destruction (e.g. in a protective mask), fuel conversion for fuel cells, and synthesis of needed compounds "in the field" that may be hazardous to ship or unavailable.

Mesoscopic pumps. While mass spectrometers and other vacuum-based instruments can often be miniaturized considerably, pumps have not kept pace with this capability. In addition, samplers for detecting vapors and particles are currently much larger than the instruments they feed. Mesoscopic pumps could greatly enhance such instruments, by allowing the entire package to be significantly

reduced in size. Research into new pump designs to increase available pressure differentials and pump rates would apply to DoD applications in instruments for sampling for explosives and chemical/biological warfare agents.

Mesoscopic power sources. In addition to chemical reactors for synthesis, combustion/power generation devices at the mesoscopic scale may be quite attractive. It appears possible to realize extremely small heat engines, turbines and other power sources that can take advantage of the markedly higher energy density of hydrocarbon fuels compared to conventional batteries. Key research issues for high-speed rotating machines at this scale are application dependent, but include the need for high-speed mechanical-to-electrical conversion, appropriate system integration methods (packaging, fuel delivery, control, start-up of gas bearings, etc.), and improved modeling capabilities. DoD applications could include person-portable power sources and distributed/redundant vehicle power supplies.

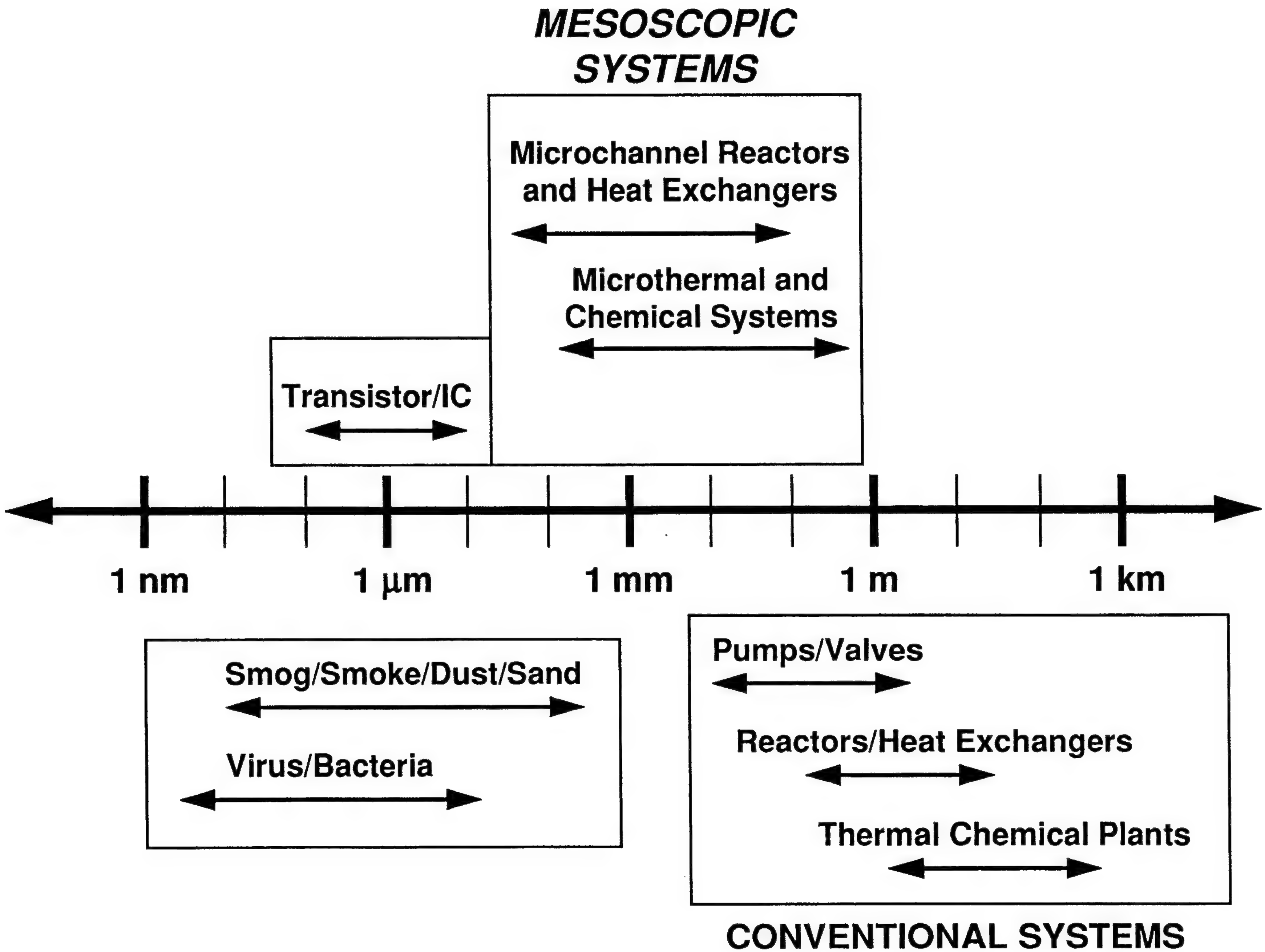
Mesoscopic propulsion/robotic systems. In this size range, significant forces can be generated for propulsion, lifting and carrying. Taking inspiration from mesoscopic animals, mesoscopic robotic systems could be developed that take advantage of favorable dynamic and static properties of mechanisms in this size range. Development of such systems would likely be accelerated by the development of suitable actuators and power sources (potentially addressed above), research into new materials and tribology issues at this scale, packaging and improved distributed control algorithms. DoD applications could include autonomous, remote intelligence gathering systems; autonomous mine, chemical/biological agent detection and neutralization devices; and improved UAV/UUV and other autonomous vehicles.

Mesoscopic thermal systems. Due to enhanced thermal and mass transport and reduced mass, high-performance heating and cooling systems could be realized at this scale. Further research would be beneficial in the areas of fluid dynamics at this scale DoD applications could include personal environmental control units, distributed HVAC systems for vehicles and large vessels, and heat engines to convert waste heat into useful energy.

Mesoscopic systems fabrication. Fabrication techniques for mesoscopic systems straddle the lithographic ones used to realize MEMS devices and "conventional" approaches used to build larger scale mechanisms. New fabrication techniques would likely greatly enhance the ability to realize fully three-dimensional components needed for such systems. Solid free-form modeling is a potentially important tool for this, and other relevant techniques might include electroforming, precision electric discharge machining, etc. Research into these fabrication methods and techniques for embedding MEMS devices should greatly enhance the performance of mesoscopic systems.

MESOSCOPIC MACHINES

Gregory Kovacs


MESOSCOPIC SYSTEMS
Microchannel Reactors and Heat Exchangers
Microthermal and Chemical Systems
Transistor/IC
1 nm
1 µm
1 mm
1 m
1 km
Smog/Smoke/Dust/Sand
Virus/Bacteria
Pumps/Valves
Reactors/Heat Exchangers
Thermal Chemical Plants
CONVENTIONAL SYSTEMS

MESOSCOPIC MACHINES

Larry Dubois, Gregory Kovacs

Objective: Explore the properties of chemical, thermal, mechanical and other systems that are scaled to the mesoscopic range, between MEMS and conventional machines.

DoD Relevance: Mesoscopic machines can greatly improve performance of chemical synthesis/destruction, thermal management, propulsion/robotic, power generation and other systems.

Scientific and Technical Summary

- Nast: cryocooler scaling.
- Martin: mesoscopic fluidic machines for vacuum generation and refrigeration.
- Jensen: mesoscopic chemical reactors.
- Prinz: scaling laws and fabrication techniques for mesoscopic machines.
- Hotelling: mesoscopic inertial machines.
- Full: animal locomotion at mesoscopic scales as inspiration for propulsion/robotics.

General Points

- **Mesoscopic machines can include MEMS structures or be formed *from* MEMS structures.**
- **Mesoscopic machines are generally more three-dimensional than MEMS.**
- **Mesoscopic machines can be fabricated with methods from MEMS and from conventional machining.**
- **Paralleling several mesoscopic machines can improve properties over a single, large machine.**
- **Many improved properties due to increased mass, thermal, momentum and electron transport.**

Mesoscopic Mechanical Systems

- Scaling moving machines down often means scaling speeds up, requiring attention to materials and design issues.
- Solid free-form fabrication (SFF), electric discharge machining, and electroforming, are particularly useful in this size range.
- Vaccuum pumps and air samplers could be significantly scaled down for portable use.
- Mesoscopic animals (the vast majority of all animals) can, by ramping up cycle frequencies, move nearly as fast as large ones.
- Miniaturized jet and other engines could enable distributed, redundant propulsion systems.

Mesoscopic Chemical Systems

- Some reactions that cannot be safely or practically run on a macro scale work well in the mesoscopic domain.
- Low site capacity (for safety), increased control, greater flexibility and high efficiency are possible in the mesoscopic size range.
- Mesoscopic reactors could be used for point-of-use synthesis or destruction of chemicals.
- Parallel mesoscopic reactors could generate macro-scale output volumes and retain these advantages as well as improved reliability through redundancy.

Mesoscopic Thermal/Power Systems

- Combustors/turbomachines can be scaled into the mesoscopic range for 100 W/cm^3 power densities.
- These systems could take advantage of the higher energy density of fuels than batteries.
- Power system weight would then be *dominated by fuel, not hardware*.
- Microcoolers/heaters could be used for personal climate control or distributed throughout a vehicle or vessel.

Opportunities

- Point-of-use chemical synthesis/destruction.
- Reactors to convert fuels to hydrogen.
- High-density, fuel-based electrical power sources.
- Vacuum pumps for mass spectrometers, etc.
- Samplers for CBW agent/explosives detection.
- Autonomous mesoscopic robots for intelligence gathering and mine countermeasures.
- Distributed propulsion for large vehicles.
- Improved UAV/UUV designs.
- Thermal managment for individuals, vehicles, etc.

Mesoscopic Machines

Workshop Organizers: G. Kovacs

July 17, 1996

8:15 a.m.	**Introduction** Greg Kovacs (DSRC/Stanford)
8:30 a.m.	**Mini Stirling Cycle Coolers** Ted Nast (Lockheed Martin)
9:10 a.m.	**Miniature Fluid Machines for Vacuum and Refrigeration Applications** Jerry Martin (Creare, Inc.)
9:50 a.m.	**Energy and Chemical Systems Miniaturization** Bob Wegeng and Kevin Drost (Pacific Northwest National Laboratory)
10:30 a.m.	**Break**
10:40 a.m.	**Meso Machines, Speculating About a New Class of Electromechanical Devices** Fritz B. Prinz (Stanford)
11:20 a.m.	**Fabrication Strategies for Mesoscopic Inertial Machines** Steve Hotelling (Gyration, Inc.)
Noon	**Lunch**
1:00 p.m.	**Animal Locomotion/Biological Inspiration Toward the Design of New Micro-Robots** Robert Full (C. Berkeley)
1:40 p.m.	**Mini Jet Engines** Alan Epstein (MIT)
2:20 p.m.	**Microchemical Systems for Chemical Production** K. Jensen (MIT)
3:00 p.m.	**Discussion**
4:00 p.m.	**Adjourn**

Mesoscopic Machines

July 17, 1996

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NEW MATERIALS FOR MEMS

A. Heuer, E. Cross, G. Kovacs

EXECUTIVE SUMMARY

Objective

The objective of this workshop was to examine new materials and means for their fabrication into devices that could enable novel MEMS DoD applications.

DOD Relevance

MEMS devices have found broad applicability in a number of DoD-relevant areas, including inertial, photonic, magnetic, thermal, and chemical sensing and ensuing actuation. Significant growth has occurred in this area, yet a number of application areas that are theoretically addressable have not been realized due to a lack of suitable materials. For example, MEMS devices for extreme chemical environments, high temperatures, high strains, high frequency electromagnetic radiation, etc., are, in some cases, held back due to a lack of suitable materials. With appropriate materials, it will be possible to develop and use sensors and actuators for these presently "out-of-reach" applications.

Summary of Scientific and Technical Issues

Prof. Mehran Mehregany (CWRU) "SiC MEMS Devices"

SiC is an attractive material for MEMS. It has a large band gap (2.2–2.9 eV depending on polytype), allowing high temperature (up to 800° C) electronics, exhibits low friction and wear, thus providing for improved contacts and bearings, and is chemically inert, allowing handling of corrosive reagents. Furthermore, reactive ion etching can be employed with standard Si processing tools, and useful passive oxides are readily formed. An atmospheric pressure (AP) CVD reactor has been constructed at CWRU to deposit SiC films on 4" Si wafers in a cold-walled chamber with *in situ* doping capability. Single crystal 3C epi films up to 2 mm in thickness are deposited on (100) Si at 1360° C using SiH_4, C_3H_8, H_2 mixtures with growth rates up to 2 µm/hr; the current films have unintentional N doping of 4×10^{17} cm^{-3}, surface roughness of 3 nm, and void formation less than $0.2/cm^2$. The single crystal recipe is also suitable for polycrystalline SiC deposition on polysilicon, although deposition at 1260° C on (100) Si also leads to polycrystalline SiC deposits.

Large area single crystal SiC diaphragms (1.5 mm thick, 1.2 cm on a side) have been fabricated, and show sheet resistance of 80 Ω/square, a resistivity of $2–4 \times 10^{-3}$ Ω-cm and electron mobilities of 850 cm^2/Vs. The mechanical properties of these films have also been determined; the single crystal films have Young's moduli of 390–440 GPa and residual compressive stresses of 200–380 MPa, whereas the polycrystalline deposits have Young's moduli of ~310 GPa and residual stresses of ~350 MP.

Applications for these SiC devices include pressure sensors, working at pressures up to 200 psi and temperatures to 500° C, shear stress sensors for wind tunnel instrumentation, and heat flux sensors. While the latter two sensors have to date only been constructed from polysilicon, bulk micromachined 3C SiC on silicon pressure sensors have been fabricated using a 7-mask process.

SiC microactuators of interest include microvalves for turbine and combustion cooling (up to 100 psi pressure at 500–800° C and air flow rate of 1.5×10^{-4} $kg/sec/cm^2$), microvalves for compressor surge/

stall control, and microvalves for combustion fuel/air control (up to 200 psi pressure at 500–800°C and air flow rate of 6×10^{-3} kg/sec/cm^2). Si microatomizers for fuel delivery have been fabricated using conventional micromachining but Si lacks the requisite erosion resistance; SiC overcoats, in addition to coping with the erosion problem, improved the flow rate and spray angles by at least 10%. Finally, lateral resonant SiC devices have been surface micromachined from poly-SiC films deposited on polysilicon using a single mask. 3 µm x 150 µm x 500 µm suspension beams separated by 3.5 µm have been fabricated, which exhibit actuation voltages as low as 30V and resonant frequencies of 20–60 kHz and work well up to 500° C.

<u>Dr. John Bernstein (Draper Labs) "Applications of Ferroelectric Films to Ultrasonic Imaging Arrays"</u>

Bernstein discussed the application of thick film lead zirconate titanate (PZT) as ultrasonic receiving elements in an acoustic retinal plane. The system was designed for imaging of marine mines in shallow turbid water, using high frequency transducer elements for object illumination, an acoustic lens for focusing, and an array of PZT monomorphs on a MEMS silicon diaphragm system as the image plane.

The PZT films, fabricated at Penn. State University, used an unconventional solvent system to permit the buildup of films to 10-12 µm thickness without cracking, well beyond the thickness range (~1µm) of conventional sol-gel processing. Tests with many different lead zirconate (PZ):lead titanate (PT) ratios in the solid solution reveal that for thick films, as in bulk ceramic materials, the morphotropic phase boundary composition 52 PZ:48 PT has superior piezoelectric and dielectric properties. It may be noted that the piezoelectric response of the films increase with thickness and go beyond that of bulk PZT, probably due to strong (001) grain orientation in the thicker films.

Finite element simulation predicts good receiver sensitivity (-220 dB re 1V/µPa) at 1 MHz for the PZT monomorph diaphragms and a capacitance (92 pF) sufficient to drive interconnect circuitry on a polyimide overlay. Since it is not possible to co-process PZT and conventional CMOS circuits on the same wafer due to temperature and atmosphere incompatibility, the acoustic array is solder bump bonded to the associated CMOS circuitry.

Measured hydrophone sensitivity in the center of a 6 x 6 array (230 dB re lV/µPa) are within 10 dB of the finite element prediction. Acoustic imaging was demonstrated in a water tank using manual scanning of the imaging elements. Conclusions are that a true "acoustic camera" can be developed using this technique, which would provide vision in turbid waters for divers, ROVs, AUVs, mine counter measures, navigation, tool positioning, oil field operations, salvage, and search and rescue missions.

<u>Prof. Michael Huff (CWRU) "TiNi Shape Memory Microactuators"</u>

TiNi shape memory alloys (SMAs) have higher actuation forces (up to 5×10^7 J/m^3) and larger displacements (up to 8% strain) than most other microactuator technologies, and require only moderate power. In thin film form, thermal diffusion limitations to actuation speed will be modest as good thermal insulation, low thermal masses, and reasonable time constants and heating power should all be attainable. The SMA transformation temperature is sensitive to composition; this must be carefully controlled but does permit device operation over a range of temperature, potentially up to 500° C.

TiNi SMA films have been deposited on both Si and SiO_2 with good adherence using RF sputtering. As-deposited films are amorphous as formed and are crystallized by heating to 550° C; Ti:Ni stoichiometry can be controlled to some extent by varying Ar pressure during sputtering. 2mm x 2

mm x 2µm diaphragms show good recovery force and recoverable strain; as-deposited films contain compressive residual stresses of ~40 MPa, which become tensile on crystallization (~40 MPa in the martensite phase and ~360 MPa in the austenite phase).

The CWRU group has done extensive TEM characterization of their SMA films, and also studied commercial SMA microvalves biased by a Cu-Be spring which exhibits fatigue (an increase in power needed to effect the SMA transformation) after 10 to 1×10^6 cycles; TEM of fatigued films implicated development of a fine dispersion of precipitates (probably Ti_2N_3) as being responsible for the fatigue.

TiNi SMA microactuator devices under study include "intelligent" microvalves, micropumps, resonators, refreshable Braille displays and optical memory storage elements. The microvalve project envisages an array of devices that combine the microvalve, flow sensor and control electronics onto a monolithic Si substrate to allow closed-loop control of fluid flow delivery. Liquid handling microvalves and smart microvalves for high temperature and corrosive environments are also under development. The primary application area is for fuel distribution systems for gas turbine and combustion engines, whereas secondary applications are for drug-infusion technologies. (A low power smart micropump for implantable insulin design delivery provides 1.2 ml/stroke and consumes 2 mJ per stroke at a pump rate of 0.25 ml/day.) Prototype valves using 2 µm thick TiNi diaphragms have employed a contact spring to bias the microactuator and have realized 90% modulation at gas flows of 600 sccm. Of course, micromachined flow control devices have the advantages of small size and weight, low-cost due to batch fabrication, and high reliability.

Prof. Manfred Wuttig (U. Maryland) "Giant Magnetostrictive Films for MEMS."

A novel new actuation scheme for MEMS involves the Giant Magnetostrictive effect, the very large coupling between magnetic fields and strain exhibited by certain magnetic materials The Terfenol-D class of alloys in bulk form have large magnetostrictive coefficients (λ) combined with near-zero magnetocrystalline anisotropy coefficients (K). (Fe_2Tb has a large positive K and large λ, Fe_2Dy a large negative K and large λ, so alloys between the two can have K values that are very small.) Wuttig has been studying amorphous and nanocrystalline films of such alloys made by RF sputtering. These films have large compressive intrinsic stresses as deposited, which can be reduced to zero by annealing to ~400° C; higher annealing temperatures lead to films with tensile residual stresses. Current output strains are ~0.2% for reasonable magnetic fields; it may be possible to increase this by of several orders of magnitude for certain novel materials that can undergo a ferromagnetic → antiferromagnetic transformation.

These films can provide magnetoelastic or magnetostatic energies between 2 and 8×10^5 J/m^3. Technologically interesting devices with static and dynamic magnetomechanical properties (good damping for example) should be possible with suitable "engineering" of magnetic domains in thin films; this engineering requires geometry control together with magnetothermomechanical processing of the thin films.

Combining the Giant Magnetostrictive film in heterostructures with shape memory alloys can provide efficient microsensors and microactuators, including those working at elevated temperatures (up to 200° C), while combinations with III-V compounds may lead to adjustable quantum-well optoelectronic or magnetic devices.

Dr. L. T. Romankiw (IBM) "A Path: From Electroplating Through Lithographic Masks in Electronics to LIGA in MEMS"

Application of electroplating technology to microelectronics and MEMS has a long (~30 yr) history and many names—Electroplating through Lithographic Masks, Through Mask Plating, Additive

Pattern Plating and LIGA (Lithographie Galvanoformung Abformung). Electronic requirements for electroplated deposits (precision, purity, small size, high aspect ratio, controllable electrical and magnetic properties and microstructure) have led to many advances in the hardware and design used for electroplating baths and understanding of the basic electrodeposition processes. Advanced electroplating has been used for printed circuit boards, connectors, chip carriers, I/O device, and for storage, memory and logic. Good understanding exists of current distributions through apertures to control the uniformity of electroplated deposits; Romankiw likes to think of metallization via electroplating as a type of room temperature injection molding, yielding structures with high aspect ratios and good resolution (μm scale features separated by 100 nm, for example). In fact, as dimensions shrink and aspect ratios increase, the patterning fidelity of plated features remain excellent and the thickness uniformity becomes easier to control (below 2 μm thickness, the plating process becomes mass transport controlled).

For high quality uniform through-mask plating, a thin seed layer is needed and solution agitation, current density distribution, cleanliness and plating bath and resist chemistry are important issues. Alloy deposits, e.g., Permalloy, can be deposited with good and well-controlled magnetic properties.

Most recently, IBM has led the HI-MEMS alliance to form magnetic micromotors with torques of 10^{-4} Nm directly on Si wafers. Rotor and stator parts have already been fabricated successfully. This alliance has shown that conventional electroplating can create very high-aspect ratio structures in Cu and NiFe using x-ray lithography, which can be planarized and will accept dielectrics; variable reluctance motors with up to 3 metal levels have been constructed.

Prof. Karen Gleason (MIT) "Pulsed Plasma Polymer Deposition"

Gleason provided an overview of new methods for the deposition of poly(tetrafluoroethylene), or PTFE-like (Teflon-like) materials through pulsed plasma or thermal decomposition of a hexafluoropropylene (HFPO) source vapor (which, under thermal or plasma decomposition, releases CF_2, which can polymerize). PTFE and PTFE-like materials have a number of excellent properties for MEMS applications, including a low dielectric constant (approximately 2, depending on stoichiometry and density), good chemical and thermal stability, low fluid permeability, biocompatibility, low stress, flexibility, and low water uptake. These properties promise to address MEMS needs in a variety of areas, as well as to provide high-performance inter-level insulators for high-speed interconnections on integrated circuits. CVD deposition of organic polymers has several advantages over other techniques (such as spin casting from solvent, dip coating, etc.), including formation of highly uniform thin films, absence of solvent usage, isotropic film properties, no outgassing/shrinkage, *in situ* adhesion promotion, and the possibility of scale-up.

Pulsed plasma CVD (pulsed PECVD) provides a new mechanism for forming high-quality PTFE films. During the RF power pulse, reactive species are generated and ion bombardment of surfaces occurs. Since the lifetimes of the ions are shorter than those of the neutral species, in the inter-pulse ("off") intervals, the neutrals dominate, and form the high quality (low dangling bond density) films from long-lived reactive species without competing ion bombardment. Pulse duty cycle, flow rate and other parameters can be used to tune the film properties (e.g., dielectric constant). The resulting films are continuous, conformal and adherent. Examples shown included coated wires tied in small radius of curvature knots and coated silicon micro-ribbon cables.

Pyrolytic decomposition of HFPO was also demonstrated, using a filament heated to 300–550° C. Again, excellent films can be obtained, and adhesion tests show excellent bonding to both thermal silicon dioxide and aluminum. Proposed sandwich structures would provide adhesion through a

lower layer of pulsed PECVD PTFE (plasma roughening should increase adhesion strength), a core layer of pyrolytic PTFE (better bulk properties), a next layer of pulsed PECVD PTFE and a top metal layer (naturally, this sequence could be repeated).

Overall, it is now possible to deposit very high-quality PTFE-like films via pulsed plasma or pyrolytic CVD. These films possess similar properties to bulk Teflon, yet can be deposited conformally and adherently over complex surfaces. Such films should find application in MEMS devices for extreme chemical environments (e.g. chemical sensors), high frequency electromagnetic applications (RF switches, transmission lines, etc.) and many others.

Conclusions and Observations

The range of materials available for sensing and actuation in new and novel MEMS devices are impressive, and such devices will find many DoD applications. Materials for extreme environments and/or improved sensing and actuation were apparent during the workshop: SiC for higher temperature and higher pressure environments; PZT, TiNi and Terfenol-D alloys for improved sensing and actuation; and PTFE for high frequency electromagnetic applications. In many cases, the processing of these new MEMS materials is compatible with Si technology (RF sputtering, APCVD, etc.) so integration with CMOS circuitry should be straightforward. In other cases (sol-gel processing of PZT), hybrid devices will be required,as the heat treatment needed to crystallize PZT is incompatible with Si processing. In fact, a deposition technology for PZT absent this limitation would be a great boon for MEMS, as would routine deposition of polymeric ferroelectrics such as PVF_2. Electroplating, while a mature technology, is capable of depositing a great range of potential MEMS materials—magnetic materials on chips for micromotors and other magnetic devices, high-temperature alloys, such as NiCr for microturbines, and FePt or FePd alloys for SMA applications. These functional materials, as well as metals with controlled thermal expansion coefficients, controlled electrical resistivities, controlled residual stresses, etc., may provide cost-effective alternatives to RF sputtering.

Unsatisfied application needs still exist for some extreme conditions, such as very high temperatures, harsh or corrosive liquids, and mechanical devices of various types with very long lifetimes; i.e., with no indications of fatigue. Efficient manufacturing processes are also needed for a wide range of materials to permit construction of MEMS devices with thicknesses much greater than those employed in normal IC devices.

There may be MEMS opportunities which do not involve IC type-fabrication tools and the MEMS community should watch out for "Si bigotry." Further, the extensive repertoire of existing materials have all been invented or exploited for applications other than MEMS. New materials development that are MEMS-specific may well be in order. It should also be noted that non-Si MEMS devices often require development times longer than for "traditional" IC devices, as the materials development must of necessity precede the MEMS device development.

In conclusion, there are many DoD applications for which MEMS provide the best if not the only solution but for which new materials are necessary. DARPA interest in such new materials should thus be strong. Specific examples include: high temperature sensors for engine/combustor monitorin; chemically inert sensors for chemical measurements in oxidizing/acidic/basic solutions; new metallic constituents, combined with low dielectric constant materials in circuits for RF applications (integrated microwave systems such as miniaturized phased array radars); high-performance sensors and actuators for mechanical MEMS devices (allowing high pressure low leak rate valves); and biocompatible materials for chronic applications (e.g., physiological measurements).

NEW MATERIALS FOR MEMS

A.H. Heuer, L.E. Cross, G.T.A. Kovacs

OBJECTIVE

EXAMINE NEW MATERIALS AND/OR MEANS FOR FABRICATION TO ENABLE NOVEL MEMS DEVICES FOR D.O.D. APPLICATIONS.

NEW MEMS CONSTRUCTION MATERIALS AND TECHNIQUES

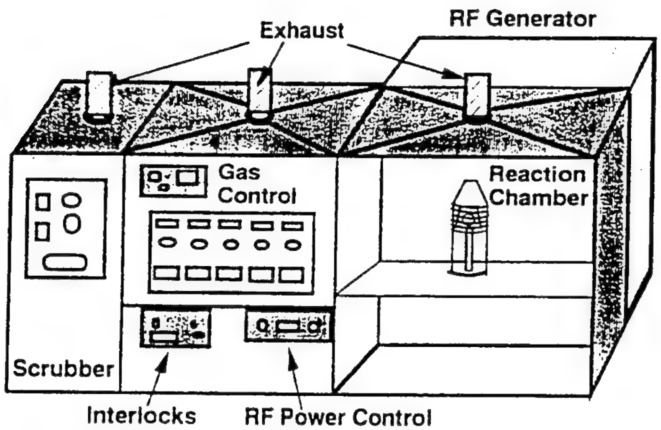
MEMS TECHNIQUE	MATERIAL/ PROCESSING
NORMAL SUBTRACTIVE PROCESSING	3C Silicon Carbide by Atmospheric Pressure Chemical Vapor Deposition
ADDITIVE TECHNIQUES	Electroplating through LIGA generated masks
	Pulsed Plasma Polymer Deposition

NEW SENSORS AND ACTUATORS FOR CONVENTIONAL SILICON MEMS

MATERIAL SYSTEM	PROCESSING METHOD
Thick-thin films of lead zirconate titanate (PZT) Piezoelectric	Modified sol-gel liquid phase Deposition
Thin film Nickel-Titanium Shape Memory Alloys	RF Sputter deposition and annealing
Fe_2Tb/Fe_2Dy Alloy films with Giant Magnetostriction	RF Sputter deposition for amorphous or crystalline films

SiC MEMS Devices

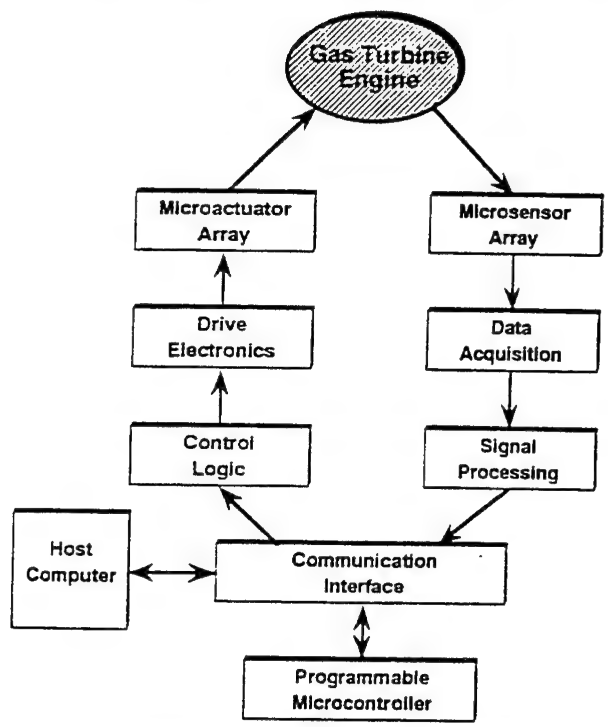
APCVD SiC Reactor



- Atmospheric chemical vapor deposition process
  - process gases: silane and propane
  - carrier gas: hydrogen
  - purge gas: argon
- rf-induction heated, SiC coated graphite suscepto holds two 4-inch Si wafers
- Vertical geometry to reduce contamination
- Cold wall reaction chamber
- *In-situ* doping capability via phosphine and dibor

SENSORS

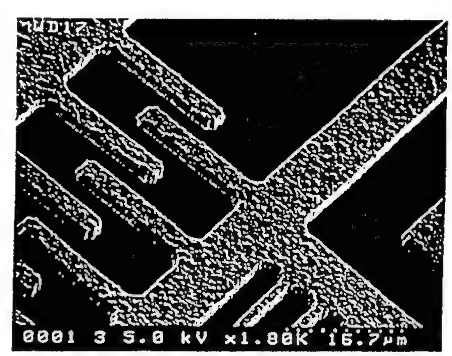
- Pressure sensors for surge/stall control
  - ambient pressure, atmospheric to 200 psi
  - pressure resolution, 0.02 psi
  - ambient temperature, 50°C to 500°C
- Ice detection sensors
  - ambient pressure, atmospheric to 50 psi
  - ambient temperature, -20°C to 5°C
  - hot gas temperature, 0°C to 300°C



ACTUATORS

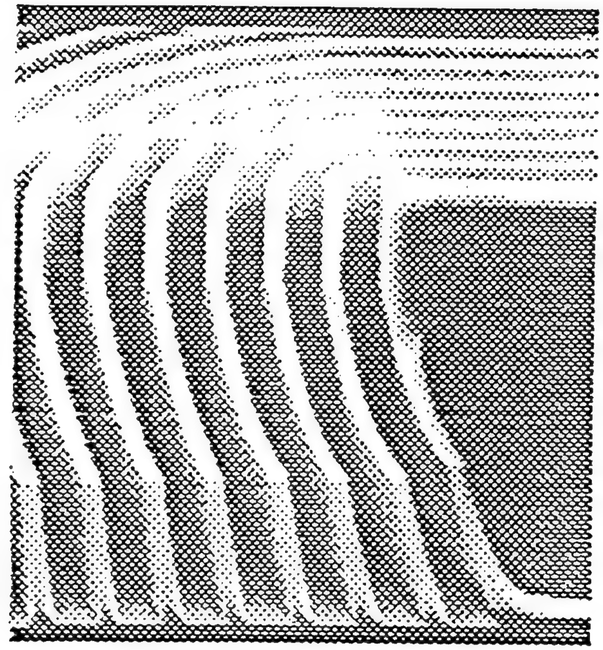
- Microvalves for turbine and combustor cooling
  - ambient pressure, 50 to 100 psi
  - ambient temperature, 500°C to 800°C
  - air flow rate, 1.5×10^{-4} kg/sec/cm^2
- Microvalves for compressor surge/stall control
- Microvalves for combustor fuel/air control
  - ambient pressure, 100 to 200 psi
  - ambient temperature, 500°C to 800°C
  - air flow rate, 6×10^{-3} kg/sec/cm^2

Lateral Resonant Devices

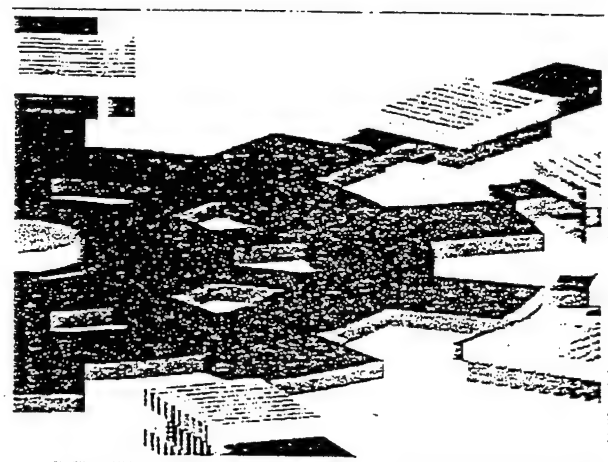


High Aspect Ratio MEMS Technology Development

manufacturing plating line in class 100 environment

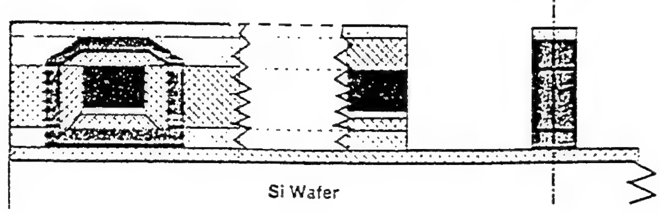


1 $\mu m \times 12$ μm photoresist for high aspect-ratio deposition



MAGNETIC MICROMOTOR

MOTOR CROSS-SECTION



Summary and Conclusions

- Considerable knowledge has been developed over the past 25 years by electronic industry. Plating became a well controlled science, capable of producing unusual structures at very low cost.
- The HI-MEMS now stands to benefit from all the breakthroughs and the high level of understanding which was achieved in developing the plating through mask technology and of the x-ray masks over the years for electronic applications.
- The electroplating and x-ray lithography are particularly a perfect match to form very high resolution 3D structures of micro or nano dimensions by:

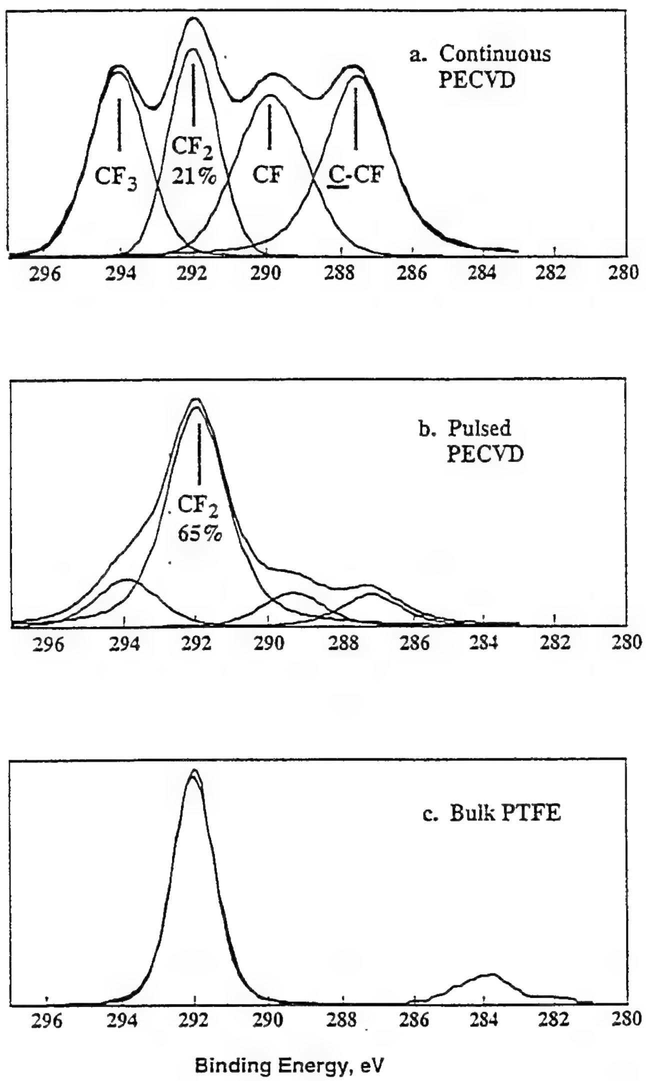
"Room Temperature Injection Molding of Metal"
Regardless whether it is under the name
"Plating Through Mask Technology"
"Additive Plating"
"Pattern Plating"
"LIGA".

PULSED PLASMA ENHANCED CHEMICAL VAPOR DEPOSITION (PPECVD) FOR POLYMER DEPOSITION

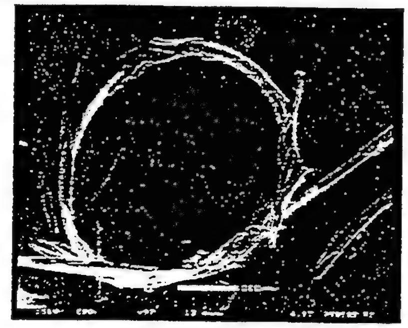
Poly (Tetra Fuoro Ethylene) = PTFE (Teflon™)

Conventional PECVD *NO GOOD*   highly cross linked (brittle films)

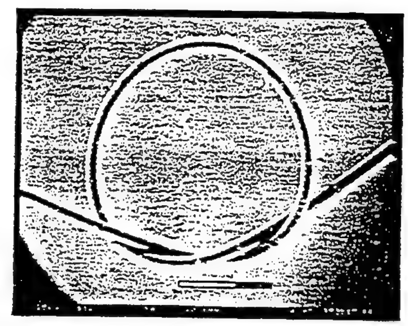
Novel MONOMER (Hexafluoropropylene oxide HFPO)



- traditional continuous PECVD

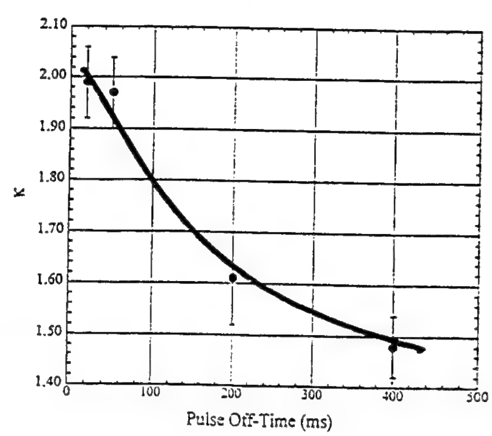


- pulsed PECVD



75 µm diameter coated wires tied in 800 µm loops

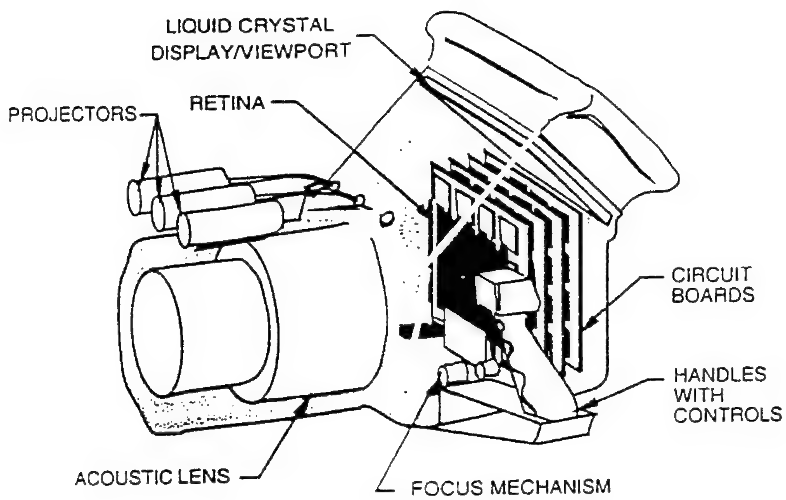
Dielectric Constant

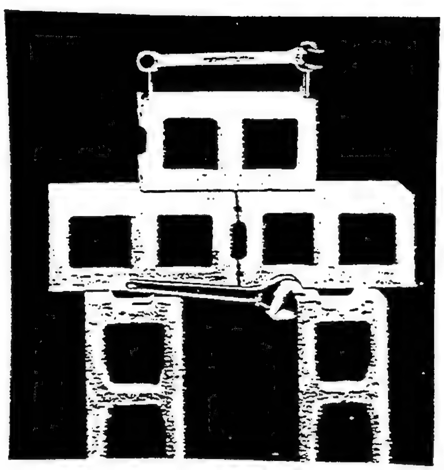


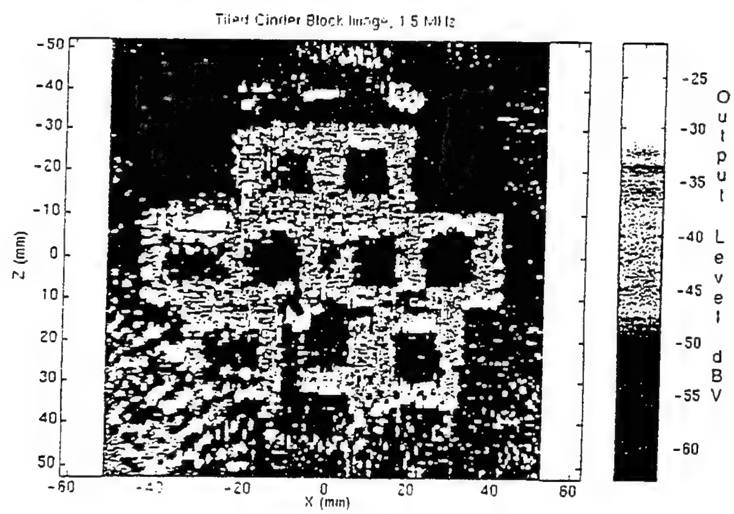
"TEFLON™-LIKE" FLUOROCARBON FIILMS HAVE MANY POTENTIAL APPLICATIONS (BIOPASSIVATION, ILD, MEMS etc.) BECAUSE OF THE UNIQUE PROPETIES OF PTFE

PULSED & THERMAL CVD PROVIDE MOLECULAR CONTROL OVER FILM COMPOSITION & PROPERTIES

DIVER'S SONAR UNIT CONCEPT - ACOUSTIC LENS SYSTEM

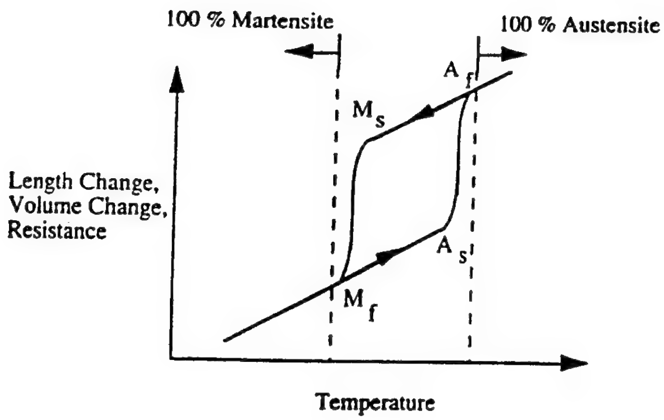


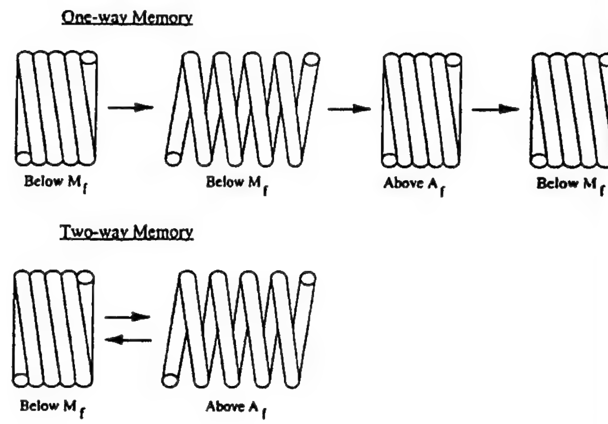




- A True "Acoustic Camera" Can Be Developed
- Sensor is Applicable to a Wide Range of Platforms & Applications
  - Divers, ROVs, AUVs, Surface Vessel in Shallow Water, etc.
  - Mine Countermeasures
  - Navigation in Turbid Water
  - Operations During Hover Near Bottom
  - Tool Positioning/Work Monitoring
  - Oil Field Operations
  - Salvage
  - Search & Rescue
  - Treasure Hunting
- Sensor Provides Vision in Turbid Waters - a Fundamental Need
- Micromechanical Hydrophones - Enabling Technology

TiNi Shape Memory Microactuators

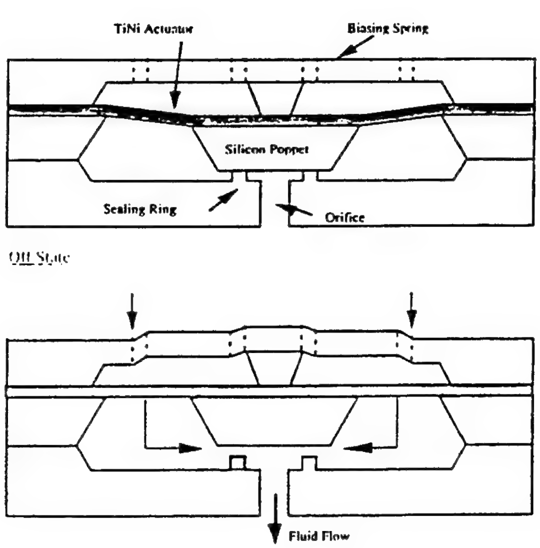




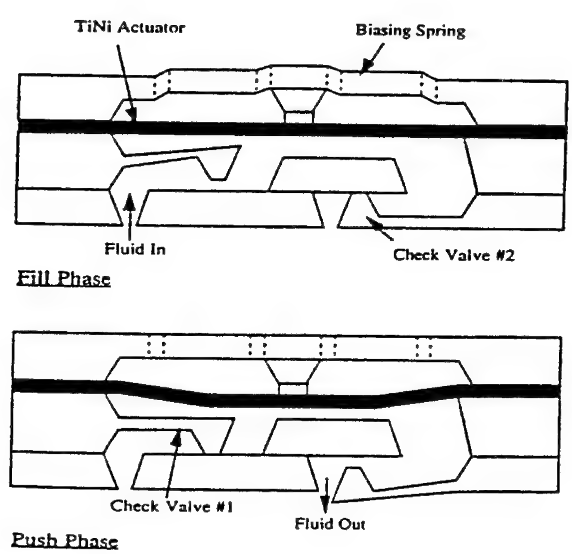
- High actuation forces (10 to 100 times higher actuation energy density than bimetallic actuation)
- Extremely high strain levels possible (up to 8 %!!)
- Phase transformation temperature adjustable with stoichiometry (M_f up to 90 C with TiNi, M_f up to 550 C with TiPdNi)
- Temperature hysteresis adjustable with stoichiometry (faster response times)
- SMA materials compatible with microfabrication
- SMAs have reasonable resistivities -- Joule heating possible

- Many of the MEMS microactuators use thermally dri processes (including bimetallic, SMA, thermopneuma
  - » Heating power = $\Delta T/R_{th}$
  - » Excellent thermal isolation possible in MEMS
  - » Thermal time constant = $\tau = R_{th}C_{th}$
  - » Very low thermal masses possible with MEMS

TiNi Shape-Memory Alloy Microvalve Design

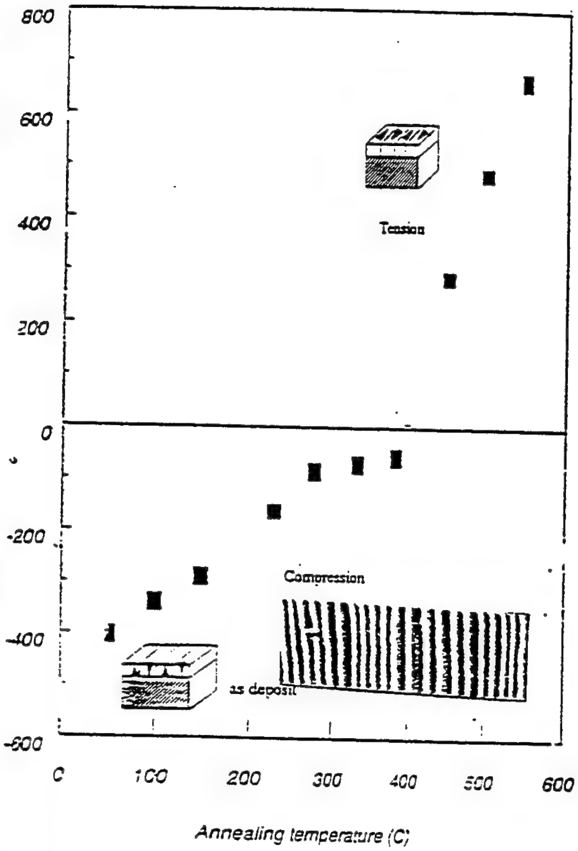


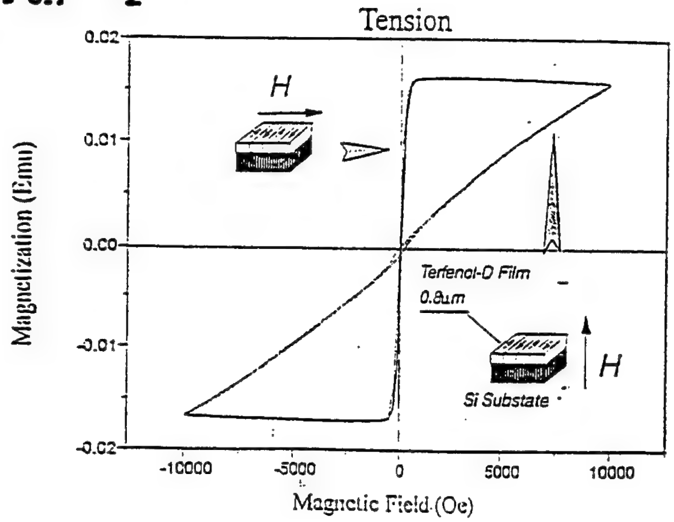
Shape-Memory Alloy Micropumps

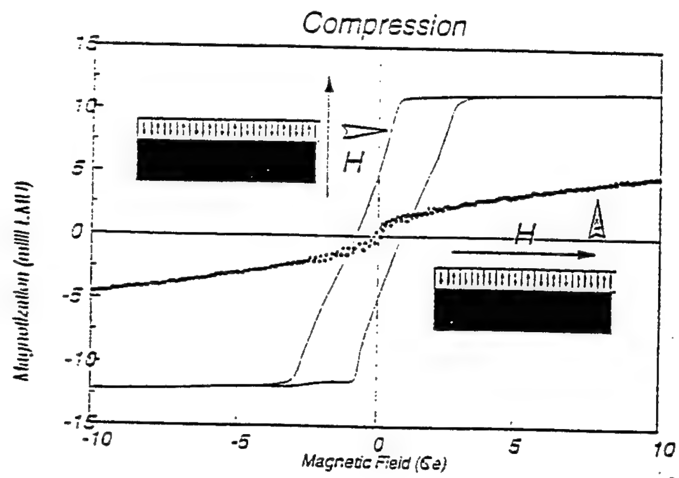


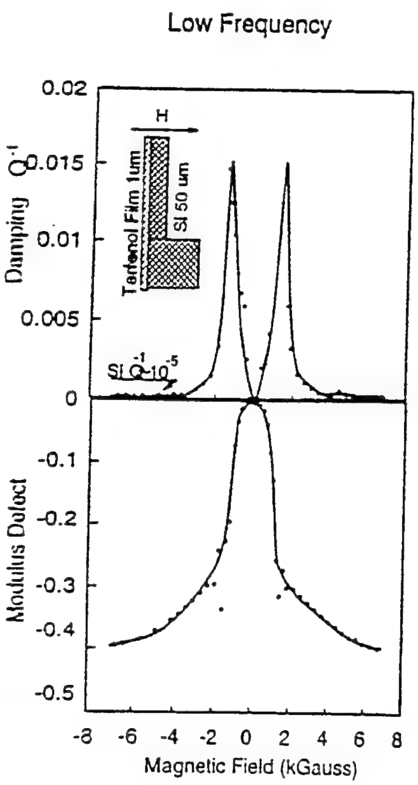
GIANT MAGNETOSTRICTIVE FILMS FOR MEMS

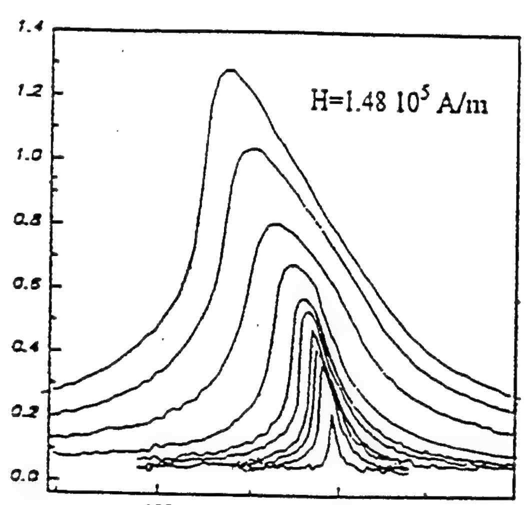
DOMAIN STRUCTURE IN TERFENOL-D FILMS
$Tb_{0.3}Dy_{0.7}Fe_2$











RELEVANCE TO D.O.D. NEEDS

<u>SILICON CARBIDE</u>
High Temperature Electronics
High Stress Applications
Erosion/Corrosion Resistant

<u>ELECTROPLATING</u>
All types of fine scale metal metal structures

<u>POLYMER DEPOSITION</u>
Electrical Insulation for VHF and Harsh Environments

MEMS for HARSH ENVIRONMENTS
Engine/Sensors/Controls
Meso-scale Motors:Micro-Turbine
Electromagnetic & Magnetostrictive Actuation
Magnetic Sensors

MEMS INSULATION
Interconnect in all types of military micro-systems

<u>Thick-Thin Film PZT.</u>
High-sensitivity unimorph
High-displacement actuation

<u>Shape Memory Films</u>
High-force micro actuators

<u>Giant Magnetostrictors</u>
Magnetic Equivalent of Ferroelectrics

Sensor/Actuator arrays
Acoustic Retina: Shallow Water mine detection

High-energy density micro-actuation
Pumps, Valves, Fuel Distribution
Microchemistry

Sensor/Actuator Arrays
Magnetically driven shape memory

SUMMARY AND FUTURE PROSPECTS

CONSTRUCTION MATERIALS

SILICON CARBIDE SiC

Essential Material: Combines high temperature strength with the possibility for high temperature electronics

Compatible with silicon processing technology

PROBLEMS:

- Materials quality, reproducibility, polytypes, accidental dopants...
- Epi Silicon Carbide on Silicon: Best of both worlds?

FUTURE:

- Diamond-coated SiC. Diamond-based MEMS?

ELECTROPLATING

Mature technology net yet widely applied with LIGA in MEMS

Essential for Electromagnetics: meso-scale motors

FUTURE:

- Deposition of Alloys, Magnetics, Terfernol
- SMA alloys FePd, FePt. High strength
- NiCr for micro turbines

PPECVD OF POLYMERS

Very attractive for TEFLON

Insulation, passivation, packaging, etc.

FUTURE:

- Confirm the very low dielectric constant
- Apply to other fluorine-based polymers; e.g., PVF2

SUMMARY AND FUTURE PROSPECTS

SENSOR AND ACTUATOR MATERIALS

PZT BASED SYSTEMS

Essential for High Frequency (MHZ) Ultrasound.
Shallow water mine hunting : Medical Ultrasound.
Combines high receive sensitivity with strong actuation capability in hybrid systems.

FUTURE:

Urgently need new processing methods compatible with IC Technology.

SHAPE MEMORY ALLOYS

"Come of age" in MEMS.
Combine high strain, high force, modest speed.
Low conversion efficiency not a major problem.

FUTURE:

Better control of composition, microstructure to lower fatigue.
High T_c alloys.

GIANT MAGNETOSTRICTORS

Controlled passive elastic damping.
High force actuation.

FUTURE:

Possible antiferromagnet:ferromagnet phase switch for massive strain.
Composite with SMA to give magnetic control.

New Materials for MEMS

Workshop Organizers: A. Heuer, G. Kovacs and E. Cross

July 18, 1996

8:30 a.m.	**Opening Remarks** Ken Gabriel (DARPA)
8:40 a.m.	**SiC MEMS Devices** Mehran Mehregany (Case Western Reserve University)
9:40 a.m.	**Applications of Ferroelectric Films to Ultrasonic Imaging Arrays** John Bernstein (Draper Labs)
10:40 a.m.	**Break**
11:00 a.m.	**TiNi Shape Memory Microactuators** Michael Huff (Case Western Reserve University)
Noon	**Lunch**
1:00 p.m.	**Giant Magnetostrictive Films for MEMS** Manfred Wuttig (University of Maryland)
1:50 p.m.	**Advanced Electroplating Technology** Lubomyr T. Romankiw (IBM)
2:30 p.m.	**Pulsed Plasma Polymer Deposition** Karen Gleason (Massachusetts Institute of Technology)
3:30 p.m.	**Discussion**
4:45 p.m.	**Adjourn**

NEW MATERIALS FOR MEMS

JULY 18, 1996

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INTERFACES FOR OPTICAL AND ELECTRONIC MATERIALS

R. Osgood, E. Hu, T. McGill, R. Rapp (DSRC)
R. Leheny, A. Husain, G. Pomrenke (DARPA)

EXECUTIVE SUMMARY

Objective

Examine several recent new materials processing technologies which are capable of atomic-scale chemical and spatial resolution for possible opportunities by DARPA.

DoD Relevance

Integration of detection, sensing, signal processing, and computation systems is a key enabler for advanced defense systems. This integration technology can lead to new "systems on a chip", an approach which will radically lower cost and size and weight of the integrated system. Many forms of O/E and electronic integrated systems for DARPA involve the need for atomic-scale perfection at interfaces. These include mixed integration of infrared sensors, epitaxial growth of mid-IR lasers, and materials for MEMS. Several recent advances suggest that the time may be ripe for attaining such atomic-level control and hence allow various forms of integrated systems. The development of such large-scale integrated systems can only be done by large interdisciplinary teams.

Summary of Scientific and Technical Issues

The speakers for this workshop covered a wide variety of new materials processing technologies for semiconductor devices, including those for electronic and optoelectronic applications. These methods were, for example, fusing or bonding together differing semiconductor substrates, realizing precise removal of a single monolayer from a semiconductor surface, and epitaxially growing precise interfaces in selective regions of the substrate.

The unifying theme of the workshop was seen, however, to be achieving single-atomic-layer control of interfaces during processing. For example, the first three talks during the workshop included a discussion of the rapidly evolving technique of wafer bonding with both Si and compound semiconductor substrates. In this case, one important thrust is to control the uniformity and electrical properties of the bonded region. New and sophisticated techniques were discussed both for probing these interfaces and for insuring the integrity of the interfacial properties. As a result, the technique of silicon bonding has become a mainline IC option for SOI chips—in fact, Motorola may be planning to introduce the technique for low-power logic. In the case of epitaxial growth, new photoemission and proximal microscopy probes have guided improvement in the compositional control at interfaces and thus achieving more abrupt delineation of the deposited layers. Such control has yielded understanding of new methods for growing very diverse interfaces; thus the Workshop heard about the growth of new metal-like (ErAs) layers on the surfaces of semiconductors which can be used for a host of new optical and electronic devices. In conjunction with this talk and that on GaN and GaSb growth, the importance of the starting surface was emphasized for materials growth. These talks demonstrated that the initial surface conditions have a major effect on the quality of the subsequent growth of overlayers on the

substrate. In some cases the mechanical properties of an intermediate flexible layer may be useful in promoting growth. It was also shown that careful probing of the interfacial layers can enable the chemistry to be controlled at the atomic level.

An important area, also covered during the Workshop, was the use of interfacial reactions for fundamental improvements in device structures. One observation was that while growth is surely key, other chemistries such as layer removal or compositional change are equally important for improving device or circuit design. An excellent example is the recent discovery of the role of selective wet oxidation of AlAs—a technique which allows ready incorporation of a dielectric layer under existing epilayers. This technique has achieved a major success in lowering the threshold current of VCSELs by an order of magnitude; applications in electronics also appear imminent. Second during the course of the Workshop a lively discussion developed on the important relation of much prior work on the growth of oxides, etc. on the surfaces of structural materials. This point was illustrated by a short talk on reactive growth of oxides ("scale") on the surfaces of metal. In this case diffusion of defects plays a crucial role in allowing the diffusion of the reactant; thus it has been shown that the presence of large-size atomic species can inhibit this growth by the pinning of these defects. Clearly these considerations have an important relation to CVD growth and surface passivation reactions in electronic materials.

Conclusions

Several important conclusions were drawn from the workshop:

1) Wafer bonding is an exciting new technology for doing integration of heterogeneous materials on a common substrate. The technique is similar in spirit to the related method of epitaxial lift off–however the substrate bond in the wafer fusion case is capable of supporting electron transport. It is clear, however, that much work needs to done on understanding its limits in terms of the resulting electronic properties of the joined materials. In addition, a clear understanding needs to be developed as to its applicability in terms of the trade-off pressure and heating in making the wafer bond.

2) Much of the work on electronics materials growth and bonding is currently done by workers who are exclusively focused on electronic and photonic materials. However based on comments by participants in the Workshop who are more oriented to mechanical or structural materials problems there are important common principles to be learned by joint efforts involving the two communities.

3) It is becoming clear that advanced device structures such as heavily scaled Si and multilayer MBE require precise control over ultrathin layers of deposited or grown material. Thus surface preparation to achieve specific chemical control over the substrate is an important enabling technology. Several promising techniques based on atomic-layer self-limiting chemical reactions have recently emerged.

4) Controlled epitaxy of GaN represents a major challenge since substrates for this material are in general severely mismatched in thermal expansion and lattice dimension. Novel growth techniques based on homoepitaxy are currently being pursued; significantly more effort is needed to solve this very difficult problem.

5) Novel material probes continue to be a major force for developing insights in the above areas. In addition, analytic techniques from more classical material studies appear to be relevant in this area.

Observations

Two major observations may be made:

1) Progress in O/E and electronic materials processing will continue to be a major enabler for new integrated systems and discrete devices which are DoD specific.

2) The progress on wafer-bonded materials systems as well as the DoD need in fully integrated mixed-technology systems makes it clear that the time is appropriate to develop demonstration modules which address key DoD missions.

Material Interfaces for Optical and Electronic Applications

R. M. Osgood, T. McGill, E. Hu, R. Rapp
DSRC

R. Leheny, A. Husain, G. Pomrenke
DARPA

New Materials for Active Optical Circuits

R. M. Osgood, D. Miller, E. Hu, M. Beasley
DSRC

R. Leheny, A. Husain
DARPA

Objective

Examine a variety of new materials and materials processing techniques for use in DoD optical and electronic integrated systems,

- **Materials Interfaces – Day 1**
- **Active Materials – Day 2**

Relevance to DoD

Integrated, multifunctional chips are key technologies for a variety of high-performance lightweight technologies

DSRC

DEFENSE SCIENCES
RESEARCH COUNCIL

New Materials for Active Optical Circuits

Workshop Organizer: R. Osgood

July 25, 1996

8:00 a.m.	**Opening Remarks** Bob Leheny, Anis Husain (DARPA), Rick Osgood (DSRC/Columbia)
8:15 a.m.	**Active Semiconductor Circuits: Applications and Future Technology** Tom Koch (SDL)
9:00 a.m.	**The Role of Silicon in Active Components for Optical Circuits** Lionel Kimmerling (MIT)
9:45 a.m.	**Break**
10:15 a.m.	**Active Components for Integrated SiO_2** John MacChesney (Lucent)
11:00 a.m.	**Active Polymers for Integrated Circuits (and Displays)** Steven Forrest (Princeton University)
11:45 a.m.	**Lunch**
1:00 p.m.	**$LiNbO_3$ Technology: Optical Circuits for Defense Applications** Fred Leonberger (Uniphase Telecommunications Products)
1:30 p.m.	**$LiNbO_3$ Technology: Active $LiNbO_3$ Devices** Leon McCaughan (University of Wisconsin)
2:00 p.m.	**Other Crystalline Materials** Henry Taylor (Texas A & M)
2:45 p.m.	**High Speed Optical Modulators in Polymers** Geoffrey Lindsay (U.S. Navy, Chemistry & Materials Branch)
3:15 p.m.	**General Discussion**
4:15 p.m.	**Adjourn**

Workshop Summary

(Day 2)

- **Semiconductor-based systems have highest demonstrated functionality. Need high process control.**

- **Oxide-based systems have very high performance in some areas, i.e. modulators. This performance enables antenna sensing program. Oxide growth key issue.**

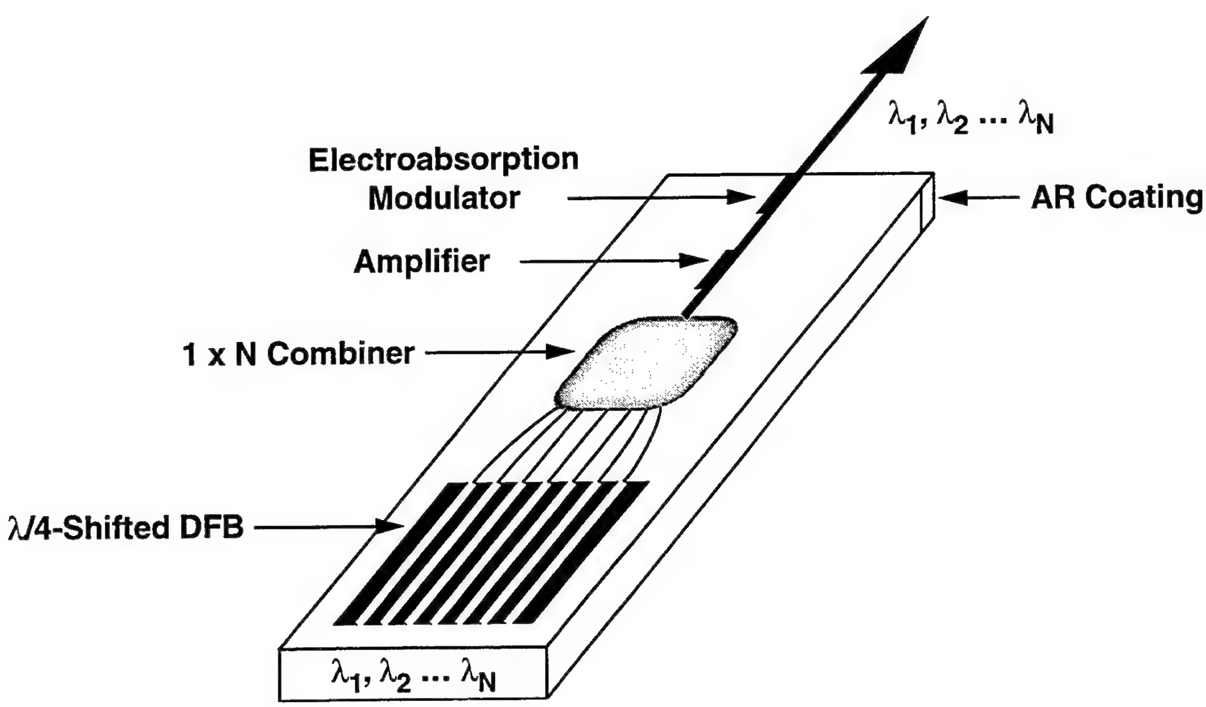
- **Organics are crucial for very large area or very low cost systems. Environmental ruggedness increasing.**

- **Limited Si/SiO_2 functionality possible.**

- **Glass-based circuits have limited functionality but are crucial for telecomm.**

III–V Semiconductors

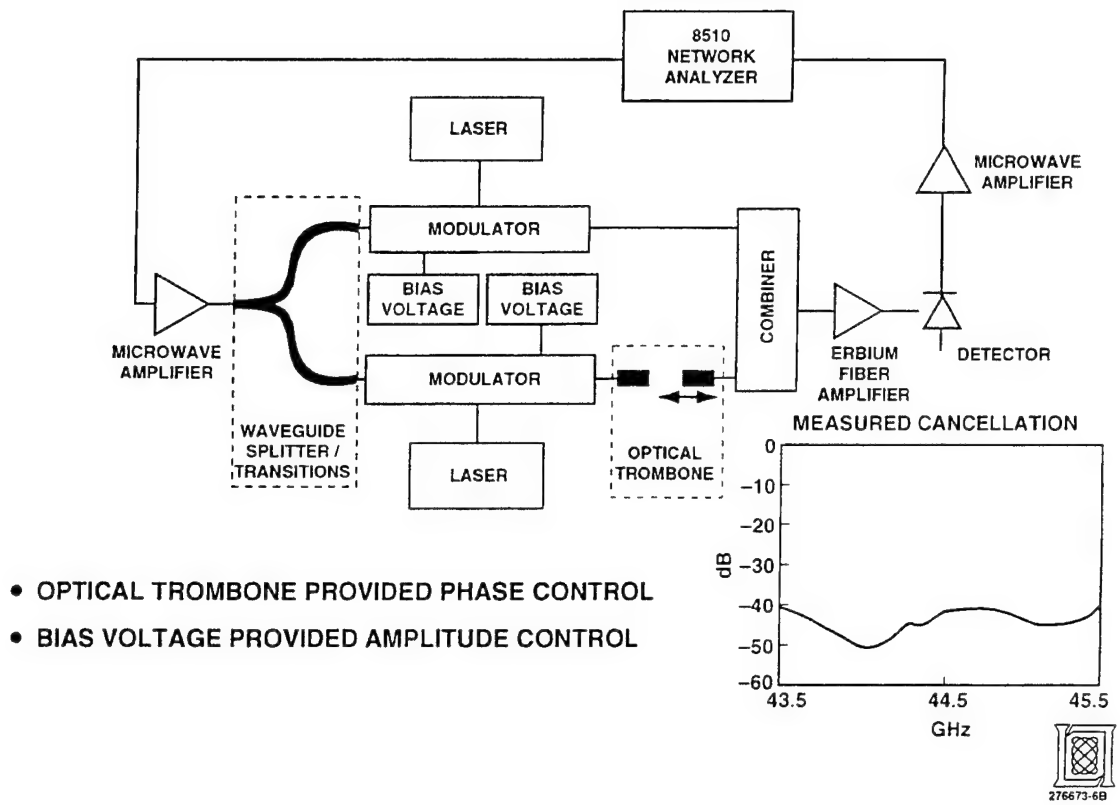
- High functionality, high performance
- Insertion loss is major engineering issue
- Applications in data communication and ϕ-array
- Integration reduces cost and insertion loss



WDM Transmitter Array PIC

Oxide-based Materials

- **High performance modulators/low insertion loss**
- **Important in RF-photonics applications**
- **Need for further "on-chip" functionality**



44 GHz Electro-optic Modulator Cancellation Demonstration

DSRC
DEFENSE SCIENCES
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New Materials for Active Optical Circuits

Workshop Organizer: R. Osgood

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Interfaces are important for many areas of electronic/optical materials processing

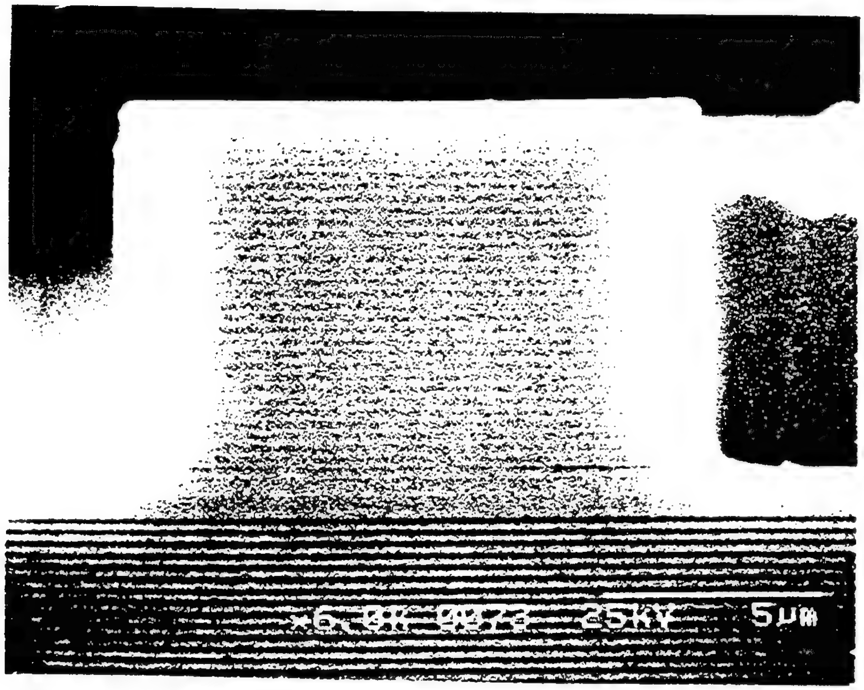
- **Surface Passivation/Preparation**
  - H-terminated Si
  - Oxide Removal III-V, II-VIs
  - Precise Etching
- **Complex Oxide Growth**
  - PZTs on Si
- **Growth**
  - Abrupt heterointerfaces
  - GaN
- **Mixed Materials**
  - MEMS/E
  - O/E
  - O/MEMS

Workshop Summary

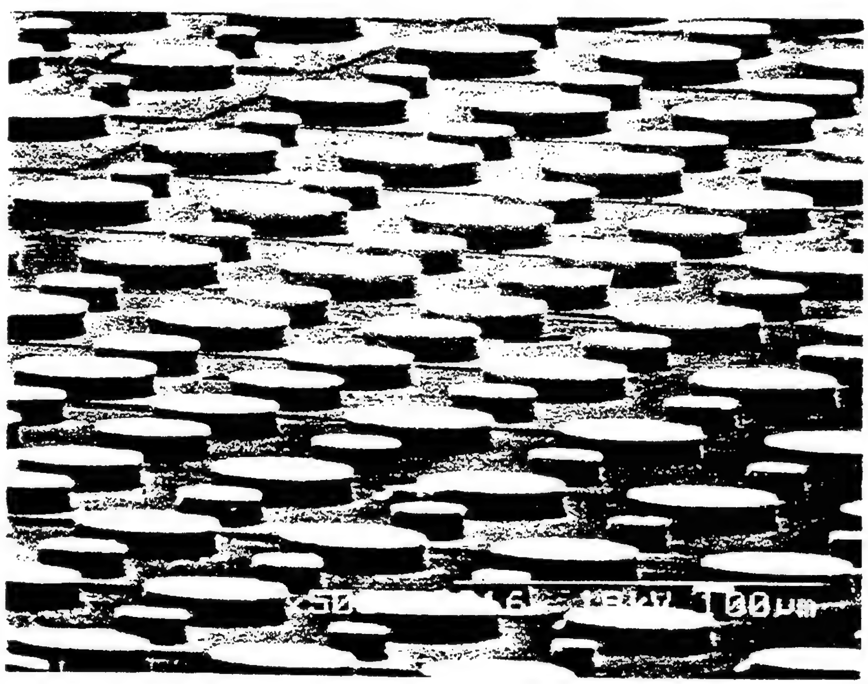
(Day 1)

- True atomic-level control over interfaces is being achieved. This control is necessary for high-quality epitaxy.
- Growth of highly sophisticated materials is being achieved; e.g., metal-like epitaxy on GaAs.
- Precisely defined insulators; i.e., SiO_2 and $AsAl_yO_x$, are becoming ever more important.
- Wafer bonding is a new approach to mixing of heterogeneous materials on a single substrate.

SEM photographs

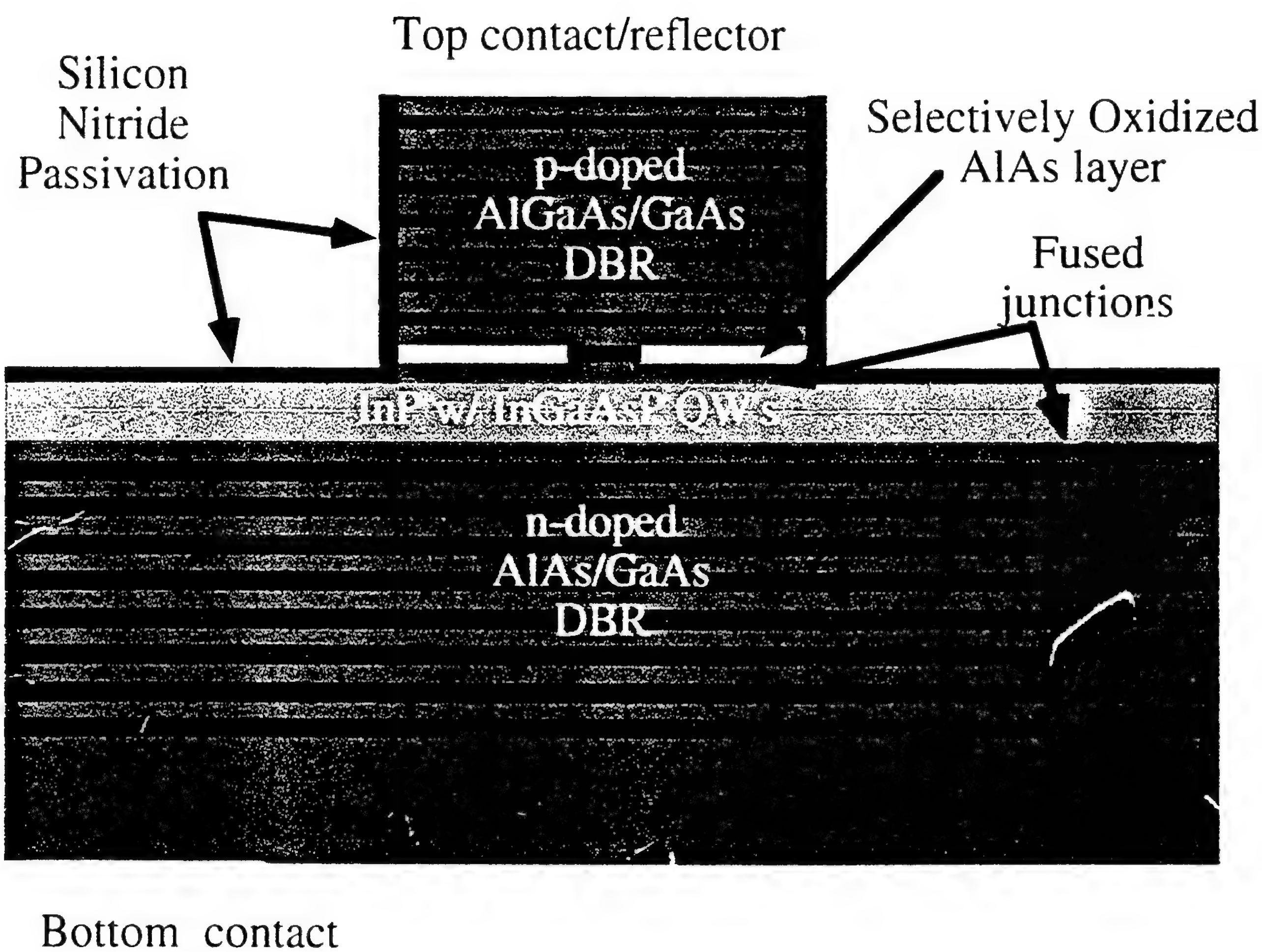


Cross-section of finished oxidized device



Top view of wafer showing high packing density

Double-fused laterally oxidized structure



Exciting Results in Mixed Materials Integration

- Wafer fusion is strong emerging technology

  Freedom to mix/match disparate materials and orientations

  Size-weight and performance advantages of monolithic

- Discrete devices are successful

- Encouraging news on "mixed" epitaxy

Summary

- The degree of functionality in optical chips is increasing.
- Sophisticated electronic and monolithic microwave chips are available.
- Solutions to combining these technologies are now available.

Observations

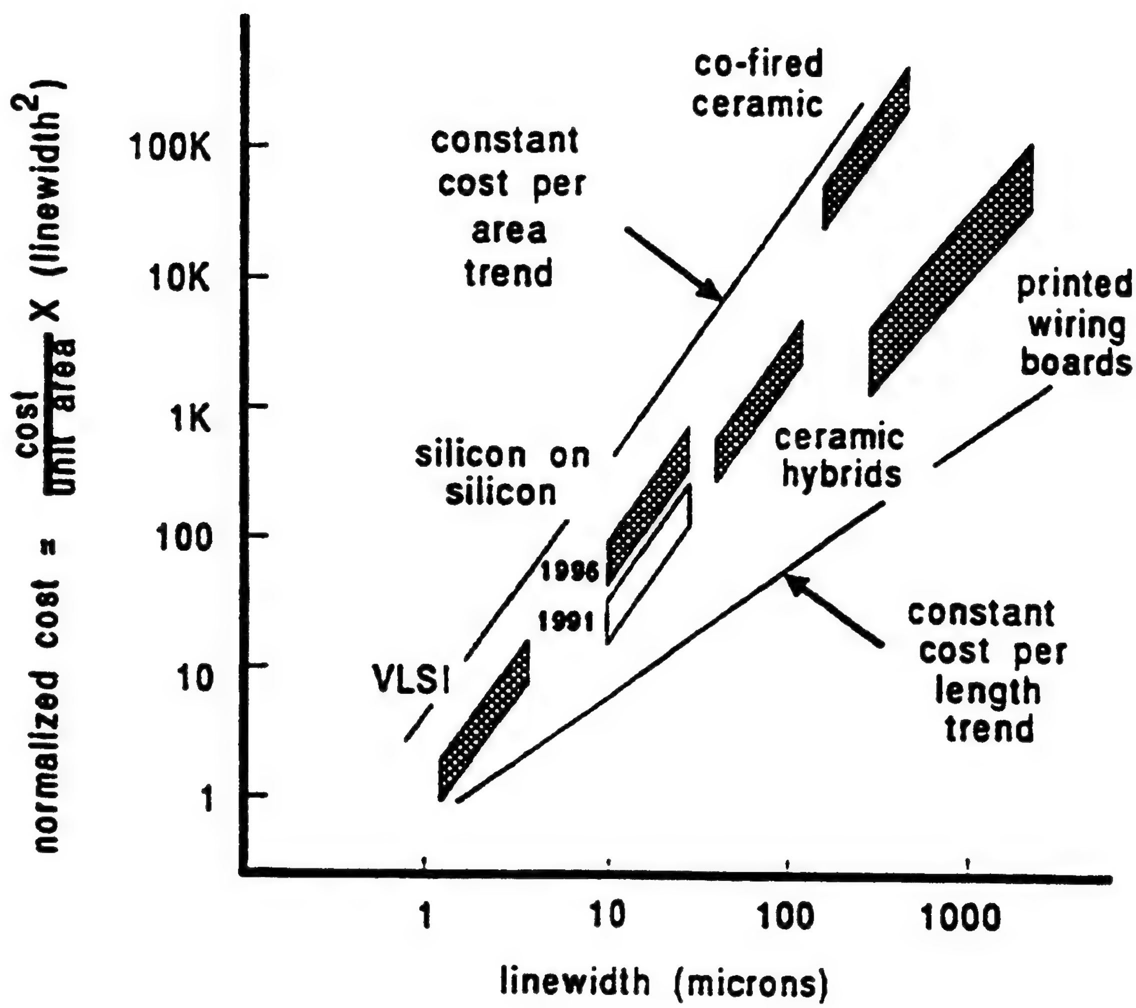
- Progress in optoelectronic and electronic materials processing will continue to be a major enabler for new DoD-specific systems

- The recent successes in some areas of wafer bonding permit miniaturization of many DoD systems. Several possible systems are suggested.

Multifunction Integrated Systems

- Drastic increase in portability
- Drastic increase in ruggedness
- Performance can be enhanced
- Cost reduction

Value of "Integration"



Robert C. Frye and Akshay V. Shah
AT&T Bell Laboratories

Potential Demonstration Systems

- GPS units integrated with inertial compatability
  - MEMS
  - Silicon
- Chemical point sensor
  - Silicon circuit
  - IR Lasers
- Direct retina projection
  - Lasers
  - Silicon circuit

INTERFACES: PHYSICS AND CHEMISTRY FOR OPTICAL AND ELECTRONIC MATERIALS

Workshop Organizer: R. Osgood

JULY 19, 1996

8:00 a.m.	**Opening Remarks** Bob Leheny, Anis Husain (DARPA), Rick Osgood (DSRC)
	I. INTERFACE ISSUES IN JOINING DISSIMILAR MATERIALS
8:15 a.m.	**Si Wafer Bonding** Marcus Weldon (Lucent)
8:45 a.m.	**Silicon Wafer Bonding as a Device Option** Cindy Desmond (NRL)
9:15 a.m.	**III-V Wafer Bonding** Z. L. Liau (MIT Lincoln Labs)
9:45 a.m.	**Break**
	II. INTERFACES IN HETEROGROWTH AND ETCHING
10:00 a.m.	**GaN-Substrate Interfaces** Tom Keuch (University of Wisconsin)
10:30 a.m.	**The Chemical Abruptness of III-V Growth** David Chow (Hughes)
11:00 a.m.	**Interface Issues in Precision Etching of III-V's** Jory Yarmoff (U.C. Riverside)
11:30 a.m.	**Truly Heterogeneous Interfaces** Chris Palmstrom (University of Minnesota)
Noon	**Lunch**
	III. DEVICE INTERFACES
1:00 p.m.	**Interfaces for Biosensors** Kalil Najafi (University of Michigan)
1:30 p.m.	**SiO_2** R. McFeeley (IBM)
2:00 p.m.	**Ga Alc AS1.c Oxides** Evelyn Hu (DSRC)
2:30 p.m.	**Discussion**
3:00 p.m.	**Adjourn**

Interfaces: Physics and Chemistry for Optical and Electronic Materials

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ADVANCED DEVICE CONCEPTS (QUANTUM COMPUTING)

M. Beasley, D. Ferry, T. McGill

EXECUTIVE SUMMARY

Objective

Theoretical physicists and computer scientists have made major claims for the potential of so-called quantum computers and cryptography. The purpose of this workshop was to assess these claims and to examine potentially practical realizations of these ideas, with an emphasis on solid state systems.

DoD Relevance

Advanced computation, secure communications and cryptography are significant issues for the DoD. The possibility of more powerful computers, more secure signals and/or the more effective breaking of encrypted signals opens the way to more effective military systems.

Summary of Scientific and Technical Issues

An algorithm is efficient if its running time grows as a polynomial of the input size. Computationally difficult problems are ones that grow more rapidly (e.g., exponentially). Some problems (e.g., turbulence and quantum mechanics) are thought to be inherently exponential. Quantum computing is thought to be a possible answer to such problems. It is a speculative new area that is evolving theoretically at a remarkable rate but has not become a well formed research field as yet. In particular, there are no well developed physical realizations of such computers. The most advanced (perhaps only) implementation is that of the laser-excited ion trap in which a 2-qubit logic gate is under investigation.

Problems solvable efficiently on quantum computers are *qualitatively* different than those solvable efficiently on classical computers. The best documented example is factorization, a problem crucial to cryptography. Error-correcting schemes for quantum cryptography are also emerging. Spin-offs in computer science in the form of novel algorithm development may be possible. However, there are as yet no clear physical implementations with advanced electronic devices. Transforming quantum computing into the solid state area may be quite difficult, as there is an important need to provide quantum mechanical coherence between both the 0 and 1 states, and to create coherent entanglement of these states. Some candidate systems have been identified, however. The leading contender presently is coupled superconducting quantum dots (or loops).

Findings

- Quantum computing is qualitatively different.
- Quantum computing is a speculative new area that is rapidly evolving, but has not yet become a well formed research field. There may be spin-offs in the computer science area in the form of novel algorithm development, but there are no clear practical physical realizations at the present time.
- Solid state systems (such as coupled superconducting quantum dots) exist that may be suitable for future exploitation, but this is still speculative.

- A major program in quantum computing will likely be begun in Japan that should be monitored closely.
- Efforts in molecular electronics in Europe appear to be much more effectively coupled to conventional electronics work than is currently the case in the U.S.

Conclusions

- DARPA should track this rapidly evolving area.
- Error correction of quantum encrypted codes bears closer examination as an early application.

QUANTUM COMPUTING AND ADVANCED DEVICE CONCEPTS

M. Beasley, D. Ferry, and T. McGill

What is Quantum Computing?

Reversible computing has been an endeavor of scientific investigation for some time. This has been studied in the guise of logically reversible Turing machines in computer science and in physically reversible machines in physics. The basic properties can be understood simply. Consider a computing machine with *n* gates (or bits). Since each gate (or bit) can be in either the 0 or the 1 state, there are 2^n possible combinations of states that describe the actual state of the total machine. We define this total state as ψ, where ψ is the state vector of the system. This state vector can be described either as an $n \times 1$ vector, in which each element is either 0 or 1 and the ith element corresponds to the ith bit, or as a $2^n \times 1$ vector in which only a single 1 exists so that the position of this 1 in the vector describes the overall state of the machine. We chose this latter description, so that the step evolution of the machine can be described by:

$$\psi(t_i+1) = M\psi(t_i), \tag{1}$$

where M is a $2^n \times 2^n$ matrix in which (for logically reversible machines) there is only a single 1 in each row or each column so that there is a unique successor state derived from a unique predecessor state. With this definition, the set of matrices {M} that represent classical digital computation is a member of the cyclic permutation group of order *n*.

Probabilistic computing machines can be introduced by relaxing the requirement on the single entry in each row and column of M, so that there is a probability pij that state ψ_j is succeeded by state ψ_i. We now require that

$$\sum_i p_{ij} = \sum_j p_{ij} = 1. \tag{2}$$

This probabilistic approach has been applied to neural networks and to cellular automata with some success. Here, the p_{ij} are real numbers, but each bit is still either definitely 0 or 1.

In quantum computing, we further relax the restrictions on the matrices {M}, and only require them to be unitary, since non-dissipative quantum mechanics evolves through a unitary operation. Now, instead of each bit being either 0 or 1, we allow a quantum mechanical coherent superposition of these two possibilities, so that

$$|i\rangle = a_i|0\rangle + b_i|1\rangle, \tag{3}$$

subject to

$$|a_i|^2 + |b_i|^2 = 1 \tag{4}$$

Further, an *entanglement* of the states is now permitted. This means that if the member of the group of matrices {M} is selected by a set of bits $\{\psi_i \mid i = 1,...,j\}$, which then operates upon the state ψ_k, $k>j$, none of the individual states can be projected from the final operation upon the state *k*. These two new principles are properties of quantum evolution, as distinct from classical evolution, and are

fundamental to quantum computing. In this sense, quantum computing is a non-classical analog approach in which there is strong correlation between the 0 and 1 state for each bit, but the bits are not forced to either extreme of value.

Why Quantum Computing?

In its early years, quantum computing was the province of a few theoretical physicists and even fewer computer scientists. However, with the discovery of a powerful method for factoring large numbers with quantum computers, interest in this new field has grown dramatically.

In general, computer scientists have classified problems based upon the manner in which the computational effort grows with the size of the problem. Factorization and the determination of prime numbers has been a problem which is known to grow faster than polynomial in time (with the size of the problem) on normal computers. In fact, it is thought that the effort grows exponentially. Turbulence and quantum mechanics are also thought to be inherently exponential in difficulty. However, it was discovered that, with a quantum computer, factorization would only be polynomial in time, and hence the problem could be solved dramatically faster on a quantum computer. Factorization is important in cryptography and therefore this result garnered considerable attention. More recently, quantum error correcting procedures for transmission of quantum encrypted codes have been proposed that might be used to extend the range of such secure transmission systems. However, while there is much interest and rapid progress in the algorithms for quantum computation, physical demonstration of the simplest quantum gate has proven to be quite difficult.

The Workshop

The DSRC convened a one-day workshop to assess the current state of quantum computing and whether this concept would find application in the world of advanced electronic devices. Four speakers on quantum computation were coupled with four speakers on physically realizable, if speculative, electronic structures (or devices) capable of performing quantum computation. The program and attendance list are attached.

Peter Shor (ATT Research) discussed the general efficacy of algorithms for quantum computing. An algorithm is efficient if its running time grows polynomial in the input size (class P). You need for P to *not* depend upon the exact model of computer being used. (Any function computable by any physical computer can be computed on an ideal Turing machine with at most a polynomial increase in running time). Problems solvable efficiently on quantum computers are qualitatively different. The best documented example is factorization. There is a small list of problems that are believed to be more efficiently solvable by quantum computers, all of which depend upon the Fourier transform. They are thought to be exponentially difficult (e.g., turbulence and simulation of quantum mechanics). For such problems, one needs a fairly large number of particles (bits), each maintained in a quantum mechanically coherent state, to create the quantum computer. The logic structure most likely to be pursued is a (quantum) gate array.

Experiments (discussed later) are producing gates that so far work with 80–90% accuracy. One needs at a minimum 1–(1/n) accuracy and less than 1/n decoherence (i.e., loss of quantum coherence in the state of the machine). Since a qubit (i.e., a quantum bit) cannot be cloned (i.e., duplicated), one must arrange encoding so that the error can be established without measuring the state itself. Remarkably, procedures to do this have been proposed!

Tycho Sleator (NYU) pointed out that the "controlled not" is the key gate (at least two bits interact in a gate) for reversible computation. He claims that one needs three inputs/outputs (three bits) to do arbitrary (reversible) classical computation. He stressed his belief that entanglement is the key to the potential power of the quantum computer. The secret of quantum computation may be in the avoidance of the probability properties of quantum mechanics.

David Wineland (NIST) has carried out experiments using ions in laser-cooled ion traps to study quantum coherence in a potential realization of a 2-qubit quantum gate. Computationally interesting systems call for 1000s of qubits. However, quantum error correcting procedures being developed for quantum cryptography might only require 10s of qubits. Several groups are working on the trapped-ion approach. Qubits are implemented as ions in the atomic trap. Rotations (a key part of the needed unitary transformations) are the easy part of working with the ions; one can apply fields to arbitrarily rotate the quantum mechanical wave function of the ion into a superposition of states. Intrinsic dephasing time on internal states of the ion (one of the qubits) is as long as 10 minutes. External states (e.g., position in the trap) providing the other qubit are much less coherent. The active region of the ion trap is a resonator at 230 MHz, with an active volume about 200 µm on a side. One needs strong field gradients to get the coupling between the fields and the atoms, and they are using two photon absorption for this purpose. Spontaneous emission times are a few millisecs. The detection mechanism is to find the probability that the internal state of ion is in the "spin" down state. Integrity of the gate depends upon the ability to create carefully timed laser pulsesæanalogous to the famous p/2 pulses of nuclear magnetic resonance. A laser "cooling" process (which puts the ion at about 1 mK) is used to prepare the ion in a well defined ground state. The gate is "clocked" by a duration of the input laser pulses. Decoherence seems to come mainly from ion motion within the trap.

David DiVincenzo (IBM) pointed out that two uses of quantum computing are for large scale computing and to understand quantum physics. However, quantum computing is hard to achieve! One needs a refined theoretical understanding, and some operating quantum gates! He enumerated fundamental requirements for quantum gates: at least 2 qubits, a means of coupling these qubits and varying their Hamiltonian (so as to achieve logic operations), the preparation of a pure initial state, high quantum coherence, an interconnection means, and high quantum efficiency measurements. Cooper pair charging effects in small capacitance Josephson junctions (or the related system of quantum quantized flux in superconducting loops) may be a possible solid state implementation. Several different approaches to solid state implementations are also being analyzed at IBM.

Kostya Likharev (SUNY) pointed out that single-electron logic as currently implemented does not preserve quantum coherence, but is based upon two tricks: an energy change larger than the thermal energy (requiring a small system), and a tunneling barrier (with high series resistance, intentionally killing quantum mechanical coherence). Under these latter circumstances, particle number is a good c-number. The presence of high resistance does not rule out reversible computation, and they have demonstrated energy dissipation below kBTlog(2).

One can also consider the inclusion of quantum coherence in such systems. One option is a set of coupled quantum dots. As the internal energies of the electrons are quantized, good coupling is possible but requires a very, very small size. A better option is the use of coupled superconducting islands, since the presence of a macroscopic superconducting condensate between the islands preserves the coherence. Quantum coherence is thus achieved with much larger size devices than in the non-superconducting quantum dots. Readout of the state by a "Bloch transistor" is feasible. Workers in the field have verified that the Josephson current can be modulated by an adjacent

electrode or gate. Problems in quasi-particle tunneling (limiting pair charging energies to less than the superconducting energy gap), random impurities (leading to random background charge), and short dephasing time (perhaps of the order of 100 ns in real tunnel junctions) are current barriers to progress. Nonetheless, superconducting dots are the most promising solid state system identifiable at this time.

Avi Aviram (IBM) discussed the history of molecular devices—one possible route to qubits. The earliest idea of a molecular device was built around the concept of a molecular quantum dot, although doping was used to define a p-n junction. Molecular "wires" have been measured using an STM tip. Molecular transistors have also been discussed by several groups. Here, an electric field induces a change in conduction paths in a crossed chain molecule. IBM has also made some more elaborate structures with molecules, grown on a surface as a self-assembled monolayer and then formed by a subsequent reaction that changed configuration in the presence of a high electric field.

John Barker (Glasgow) reviewed the European program in molecular electronics. They are pursuing single electronics within a molecular framework and are also looking at biological and chemical sensor applications. The European effort is a sizable, coordinated program.

Molecules can be made to do logic, but are not wired up the same way as in conventional electronics. Self-assembly by inter-molecular forces is a form of seeking high level logic units, not traditional wires and transistors. The biosensor area has tried and failed in many ways due to trying to get quick and dirty systems. More recently, considerable progress is being achieved through steady, hard work. One cannot make a direct leap into massive systems without building up the basis for the technology. Future program efforts will seek practical routes to molecular scale electronics—we can build nearly anything, but can we connect it? Barker cautioned that the large number of internal degrees of freedom in large molecules does not auger favorably for a high degree of quantum mechanical coherence.

One important observation is that the molecular electronics efforts in the UK are much better coupled to the conventional electronics community than in the US. If early applications present themselves, they seem to be well suited to exploit them.

Yoshi Yamamoto (Stanford) discussed the efforts of his group on quantum coherence and quantum wires. He emphasized that microscopic systems are easier to isolate from the rest of the world and hence are robust, whereas macroscopic systems are more difficult to isolate and maintain quantum coherence. He pointed out that the robustness of a single particle interferometer is at the heart of the quantum cryptography use of quantum coherence. Quantum effects become natural and robust: a single photon or single electron is used as an information carrier; a single atom is used as an emitter, receiver and nonlinear element. This leads to quantum coherent transport at room temperature (quantized conductance), single electron charging (SET) and linear superposition states (Rabi oscillations). Quantum conductance can be seen at room temperature in a number of metallic contacts.

He also has been trying to construct a quantum wire by controllably removing H atoms from surface of H-passivated surface using scanning probe techniques. This will allow a chain of loosely coupled electrons to exist on the surface, and this may produce an atomic wire.

Findings

Efforts are already beginning to try to map ideas from quantum computers into the field of classical computer science in the design of algorithms. However, there remain questions as to whether this will be fruitful. Questions also exist as to whether or not entangled states are fundamental to

quantum computing: is this a theorem or only a "best guess?" In any event, the ideas of quantum computing are making major statements about cryptography. It seems to be widely accepted that a quantum encrypted signal cannot be broken if it can be transmitted without decoherence--a distance limitation. A novel concept in this area is the idea of a quantum error correcting repeater, in which 5 qubits, using a 25 step algorithm, can form the simplest replication of an input qubit.

Transforming quantum computing into the solid state area may be far more problematic. While the Bloch transistor may be feasible with superconducting quantum dots, there are few other suggestions for gates with good quantum coherence that do not use lasers to achieve logical switching. Molecular electronics has a number of significant opportunities for novel advanced devices, but may not work for quantum computing, since there is no obvious manner in which to incorporate the quantum phase in current approaches. Finally, laser excited quantum gates, may be the natural approach (photons to photons) in optical communication circuits to optical quantum gates and transmission systems.

- Quantum computing is qualitatively different.
- Quantum computing is a speculative new area that is rapidly evolving, but has not yet become a well formed research field as yet. There may be spin-offs in the computer science area in the form of novel algorithm development, but there are no clear practical physical realizations at the present time.
- Solid state systems (such as coupled superconducting quantum dots) exist that may be suitable for future exploitation, but this is still speculative.
- A major program in quantum computing will likely be begun in Japan that should be monitored closely.
- Efforts in molecular electronics in Europe appear to be much more effectively coupled to conventional electronics work than is currently the case in the U.S.

Conclusions

- DARPA should track this rapidly evolving area.
- Error correction of quantum encrypted codes bears closer examination as an early application.

Advanced Device Concepts

(Quantum Computing)

M.R. Beasley, D.K. Ferry, T.C. McGill

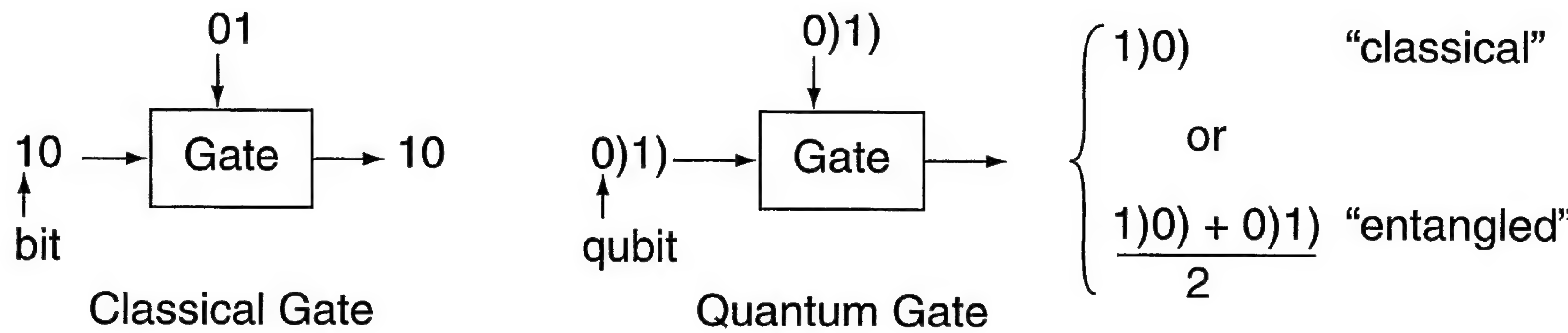
Objective

- To assess recent claims for quantum computing

Relevance to DoD

- Possibility of more powerful computers
- More effective classical code breaking—factorization
- Longer range, secure quantum encrypted code transmission

What is quantum computing?



Existence of entangled states thought to be at heart of the power of quantum computing.

Number of quantum coherent operations = $\dfrac{\tau_\phi}{\tau_s}$

τ_ϕ = decoherence time τ_s = switching time

What is quantum computing good for?

Theoretical hope:

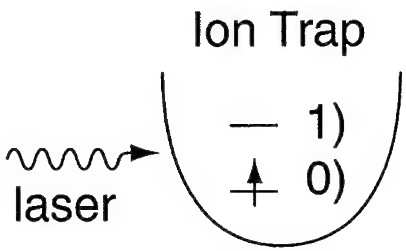
- Solve inherently hard (exponential) problems
  e.g. turbulence and quantum mechanics

Theoretical reality:

- Factorization of large numbers (1000's of gates)
- Error correction for transmission of quantum encrypted codes (10's of gates)

Physical Realizations

- **Atomic systems – Coherence high, logic awkward, physical size large**

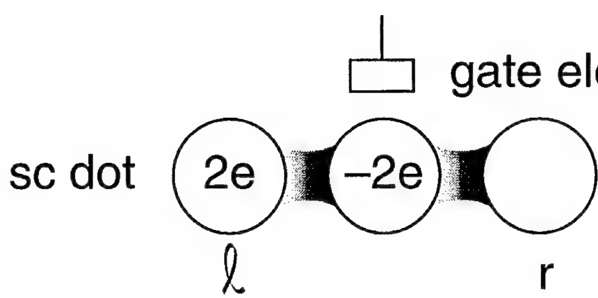


$$\text{2 qubits} = \begin{cases} \uparrow),\ \downarrow) & \text{internal to ion} \\ 0),\ 1) & \text{vibrational modes of ion} \end{cases}$$

Prototype gate under study

- **Macroscopic systems – Coherence lower, logic easier, microcircuit size**

Coupled superconducting quantum dots (or loops)



1 qubit = $2e)_{\ell}$, $2e)_{r}$

Prototype gate conceptualized

Findings

- Quantum computation is qualitatively different
- Physical theory and computer science rapidly evolving
- Physical implementation of quantum gates beginning
- Solid state implementations conceivable
- A major program in quantum computing will likely begin in Japan
- Efforts in molecular devices in Europe better coupled to conventional electronics efforts than in U.S.

Conclusions

- DARPA should track this rapidly evolving area
- Error correction for transmission of quantum encrypted codes bears closer examination as an early application

Advanced Device Physics Concepts

Workshop Organizers: D. Ferry, M. Beasley and T. McGill

July 22, 1996

8:30 a.m.	**Status of Quantum Computation** Peter Shor (IBM)
9:15 a.m.	**Quantum Logic Gates** Tycho Sleator (NYU)
10:00 a.m.	**Break**
10:15 a.m.	**Applications of Trapped Ion Quantum Logic** David Wineland (NIST)
11:00 a.m.	**Pros, Cons and Needs of Quantum Computing** David DiVincenzo (IBM)
11:45 a.m.	**Lunch**
1:00 p.m.	**Prospects for Quantum Coherent SET Devices** Kostya Likharev (Stony Brook)
1:45 p.m.	**Molecular Devices** Avi Aviram (IBM)
2:30 p.m.	**Molecular Electronics** John Barker (Glasgow)
3:15 p.m.	**Break**
3:30 p.m.	**Artitical Quantum Wires** Yoshi Yamamoto (Stanford)
4:15 p.m.	**Discussion**

Advanced Device Physics Concepts

July 22, 1996

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ADVANCED LITHOGRAPHY

G. Fuller and T. McGill

EXECUTIVE SUMMARY

Objective

The objective of the advanced lithography workshop was to explore new techniques for lithography beyond the current standard directions in lithography. The last general DSRC workshop on advanced lithography technology was held in July 1993, and an update focus session on phase shift masks for optical lithography was held in July 1994.

It now appears almost certain that standard optical lithography will prevail down to at least 130 nm features, which is the nominal feature size for 4 gigabit dynamic RAM chips. With the addition of various enhancements now becoming available it is likely that advanced optical lithography will even reach toward 100 nm feature sizes.

Extensions of optical lithography will thus carry the patterning load for some time into the future. However, an examination of technology trends, as exemplified by Moore's Law or the National Technology Roadmap for Semiconductors, shows that some new lithography technology must be ready and available for production use within 10 years.

The overall objective for this workshop was to explore approaches and research topics for creating useful lithography capability in the 100 nm range and smaller.

DoD Relevance

Lithography technology is the key enabler controlling the scaling and degree of integration for silicon semiconductors. This integration in turn drives the size, weight, cost, reliability, and capability of DoD electronic systems.

Of special interest to the DoD is the relatively weak domestic lithography infrastructure, with potentially adverse implications for reliable and timely availability of leading edge lithography technology. There has been a strong trend over the past decade for the major suppliers of lithography exposure tools and supporting technologies to be located outside of the United States.

An emerging interest for the DoD is driven by the "gap closure" in semiconductor technology now underway in defense systems. Historically many electronic components used in defense systems were custom designed and manufactured, with the result that overall levels of silicon process and patterning complexity tended to lag behind commercially available technology. With both the transition to more commercial content in military systems and the reduction of the technology lag, it is becoming increasingly important for the DoD to assure the availability of world leadership semiconductor technology.

Scientific and Technological Summary

It is now highly likely that conventional optical lithography will carry the bulk of the semiconductor patterning load for the next 7 to 10 years, down to pattern sizes of 130 nm to 100 nm. The 1994 National Technology Roadmap for Semiconductors (so-called SIA Roadmap) predicts that 130 nm chips will be manufactured in 2004 and 100 nm chips will be manufactured in 2007. After

conventional optical lithography reaches its limits there are a number of contenders for mainstream lithography, such as Extreme UV, Cell Projection E-beam, Ion Projection Lithography, 1X Proximity X-ray, SCALPEL, and so on. However, since a major change in lithography technology is needed late in the next decade, new lithographic methods need to be explored, including maskless lithography. As the ultra devices of that time frame are introduced, lithography techniques capable of producing 25-30 nm structures may be required.

The issues and problems associated with thin membrane mask technology are well known and will not be repeated here. Many of the potential replacements for optical lithography employ some sort of thin membrane technology, and therefore are subject to these problems. It therefore is particularly appealing to examine lithographic techniques that are maskless, self-organizing, or employ robust mask technology.

A key theme of the workshop was the required information content and data transfer rate in any future lithography technique. It is well known that performance demands for electronic devices and circuits are driving chip sizes up and feature sizes down, but an equally important trend is the dramatic shrinking of patterning tolerances.

Conventional CMOS transistor structures are critically dependent on precise control of the channel length for both drive capability and leakage current. Typical historical gate length tolerances of up to 20% have now been shrunk to 10%, and there is a strong push to further shrink these tolerances down to 5% or less. This tolerance reduction is occurring even as the gates themselves are shrinking rapidly. In order to provide the demanded tolerances it is necessary to rapidly increase the number of sub-elements or pixels in the lithographic image. This requirement is completely independent from the lithography technique, but the practical solutions depend strongly on the lithography chosen.

An added complication in many lithographic techniques is the emerging used of custom shaping of the lithographic input pattern in order to get a more exact final pattern on the wafer. In optical lithography this shaping results from optical proximity correction and phase shift masks. In e-beam lithography the necessary proximity correction causes a great increase in the input data, and therefore the information content of the lithographic system. Even in "high resolution" mask-based techniques, such as ion projection or x-ray proximity, it is becoming necessary to add extra information to the mask to get the desired final pattern. In ion beam this extra information comes from the need for complementary masks to handle arbitrary patterns, and in x-ray the extra information comes from the correction of the absorber pattern needed to obtain precise image placement.

An estimate can be made of the minimum data required for 100 nm lithography. The requirement for arbitrary placement of 100 nm features on a 300 mm wafer requires over 10^{14} pixels per wafer. Considering that a conventional standard for throughput is 60 wafers per hour, this requires a pixel data rate of over 10^{12} Hz.

Any pixel-based lithography scheme, whether optical, e-beam, scanning probe, or whatever, is subject to this data rate issue. Massively parallel approaches divide the physical and/or mechanical problem, but the overall information and data rate must still be accommodated.

A comparison can be made to conventional photomask writing employed widely today. The data volumes are large, but the writing times are on the order of two hours or more. Thus the data rates are not a major problem.

Specific technologies considered in the workshop were:

- Maskless
  - Scanning probe lithography, specifically scanning tunneling microscopy (STM)
  - MEMs-based multiple e-beam lithography
  - MEMs-based optical lithography
- Masked
  - Extreme UV lithography
  - Nanoimprint lithography
  - Self-assembling lithography

Scanning probe lithography has extremely high resolution, at the atomic scale, but pattern transfer and low throughput are key issues. Excellent progress in the use of hydrogen passivation and de-passivation of bare silicon surfaces has been demonstrated as a useful resist strategy. Recent work at the University of Illinois on the use of deuterium instead of hydrogen shows even more promise as a useful resist material. The throughput issue is being pursued through the use of many parallel STM tips. Recent work at Stanford University has demonstrated the fabrication of 50 parallel tips.

It is becoming clear that scanning probe lithography may be viable for special applications, but there is still a large gap in throughput and versatility for scanning probes to be used for mainstream lithography applications.

MEMs-based massively parallel e-beam lithography continues to show interesting potential for mainstream sub-100 nm patterning. Excellent progress has been made in the microactuators needed for scanning the multiple e-beam emitters. The key challenge in this approach is the development of suitable e-beam emitters. Uniformity, high output, and long lifetime are significant issues.

MEMs-based optical lithography, fashioned around the digital micromirror devices developed at Texas Instruments, is an interesting maskless approach. It does not require high vacuum, atomic tolerances, or special photoresists. However, resolution beyond 100 nm and overall system data rates are still major concerns.

Extreme UV lithography has been under intensive research and early development in a program led by Sandia National Laboratory and Lawrence Livermore National Laboratory. The progress has been outstanding to date, and many of the fundamental feasibility questions have been answered. There are a lot of challenges remaining in the areas of defects, precision optics, and photon sources, but the basic technology issues are understood. It is yet to be demonstrated that a technically and economically viable lithography system can be developed for 100 nm patterning.

Nanoimprint lithography is a novel patterning approach based on the ancient process of embossing. This sort of stamping pattern transfer is widely used for such products as compact disks, but only recently has it been demonstrated that nanometer scale features can also be created by imprinting. Resolution and pattern precision are well demonstrated, but precise overlay of multiple pattern layers and control of defects have not been demonstrated. At the very least nanoimprinting technology should be useful for single-layer patterns. These patterns could be employed for special device applications or they could be used to provide a fiducial reference for subsequent patterning by other techniques.

Self-assembly is an interesting concept in that somehow the patterning structures "know" how to arrange themselves on a substrate. A number of interesting structures have been demonstrated, many with unique properties that would be difficult or impossible to create in any other manner. The key challenge for semiconductor applications is to create a technology that produces exactly the desired patterns and structures. In other words complex programming, such as the patterns in a microprocessor, is not yet understood. The alternative is to create semiconductor chips that are built

around or can adapt to standard physical elements. In effect this may be some sort of physical analog to a gate array. Another potentially useful role for self-assembly would be to create a reference structure for resists, substrates, thin films, or other elements of semiconductor chips.

Key Observations and Conclusions

General

Lithography scaling is continuing with no signs of falling off the traditional Moore's Law trends.

Estimates by device experts predict that CMOS technology will be useful down to at least 30 nm dimensions. Therefore it is essential that a lithography technique be developed that can economically provide patterning capability beyond optics, from 100 nm down to 30 nm.

The development time required for a major change in lithography technology is more than 10 years. As an example, the first demonstration of a 248 nm deep UV lithography exposure system was made at AT&T Bell Labs in 1985. Only in 1996 have production-worthy deep UV exposure tools started to emerge for 0.25 micron patterning. The next generation, with a wavelength of 193 nm, was first demonstrated at MIT Lincoln Labs in the late 1980s. It is estimated that production-worthy exposure tools for 0.18 micron patterning will not be available before 1999 or 2000.

Both of these examples required significant innovation, but they are still basically extensions of existing technology. The time to research and develop a completely new technology for sub-100 nm patterning can be expected to take considerably longer.

Technology

Pixel-based lithography schemes will require THz (10^{12}/sec) rates for economic viability for mainstream semiconductor applications. The pixel transfer rate is exploding in terms of creation of pixels, transfer of pixels, and inspection of pixels.

MEMS technology enables many potential new lithography approaches. Precision micromechanical structures are central to many pixel-based schemes.

Smart substrates and smart resists may be a solution to the advanced lithography challenge. We need to consider smart chips vs. loading all information on the chip up front. Adaptive processing can minimize lithography requirements. Is it easier to make 10^{12} widgets at 90% yield or 10^9 widgets at 100% yield? Many small structures might be cheaper than a few complex structures due to margins and redundancy.

We need to look at chemical engineering "tricks" to aid lithography, such as self-alignment.

Applications

There are multiple applications for advanced lithography. We need to be clear about targets when discussing technical approaches.

We need to think of new ways of adding information to chips, such as compression. This could help address the data rate problem noted above.

We need to consider "low cost" replication techniques to be applied to complex IC structures. Optical or other mask-based lithography has this characteristic. We do not want to completely lose this if a pixel-based lithography prevails.

Precision and accuracy requirements from CD control and overlay needs are greatly increasing the information content on masks and wafers. These requirements are increasing faster than a simple scaling of the number of pattern features.

We need to understand what can be tolerated with respect to errors and defects. Self-correcting or adaptive techniques would be extremely useful. How good is good enough?

We need to look at advanced lithography as an information transfer problem. Deterministic logic sets the environment today. Should we go beyond? Does lithography lead or follow logic architecture changes?

Research Strategy

We must focus on research, not commercialization. We should not worry about the "next stepper". Development can (and should) occur only when industry "buys in".

The time scale for lithography tool research and development is growing. It is estimated that development of a new lithography concept will take longer than 10 years.

The research to development transition is very expensive. It may be on the order of $1B or more to commercialize a new lithography technology.

Fair shares are not the same as equal shares with respect to research funding. Not all promising ideas cost the same to research or have the same research payoff.

Suggestions for DARPA Consideration

Extreme UV Lithography has demonstrated excellent progress and potential in the research and early development stages. It is clear that it is not the role of DARPA to heavily fund the further development and commercialization of this technology, but DARPA is in a unique position to assist in national planning for how this technology may be developed for beneficial use in 100 nm patterning and beyond. Research funding for certain elements, such as multilayer coatings and precision reflection optics may be appropriate for DARPA support.

Scanning probe lithography appears to have strong potential for extremely high resolution patterning. There are several important research questions topics requiring support. In particular, the pattern transfer mechanism ("resist") is still quite limited for general lithography purposes.

A key challenge in the pixel-based approaches is the uniformity and lifetime of the multiple sources. An additional significant issue is the data rate problem and the information content in patterns. Novel approaches to self-correcting patterning is an important topic for research.

Nanoimprint lithography has excellent potential for certain classes of patterning, especially for large area, high resolution single layer patterning. An important application would be massively parallel magnetic memory devices. Continuing research is needed on the topics of large area patterning, image placement and overlay, and defect mechanisms and control.

Self-assembling structures continue to be an intriguing concept worthy of further research. One of the most important issues is defining arbitrary patterns, such as required by typical semiconductor chips. An area that could be very well served by self-assembly techniques would be "smart resists" and "smart substrates". These could in turn provide self-correcting patterning and could lead to significant reductions in the stringent pattern sizing and positioning requirements now anticipated for 100 nm patterning.

Advanced Lithography

Gene Fuller and Tom McGill

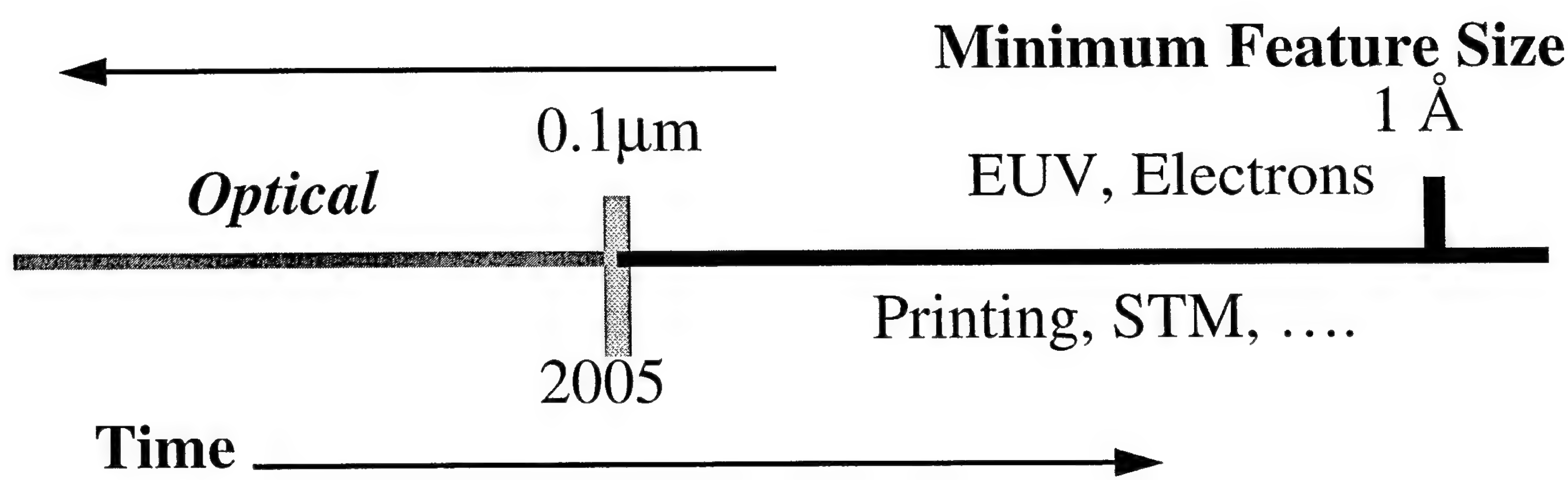
Objective

To explore new techniques for lithography beyond the current standard directions in lithography. Specific interest in approaches and research topics for feature size in the 100 nm range and smaller.

DoD Relevance

Lithography technology is the key enabler controlling the scaling and degree of integration for integrated circuit chips. This integration in turn drives the size, weight, cost, reliability, and capability of DoD electronic systems. With the transition to more commercial content in military systems, it is becoming increasingly important to assure the availability of world leadership semiconductor technology for DoD use.

Advanced Lithography



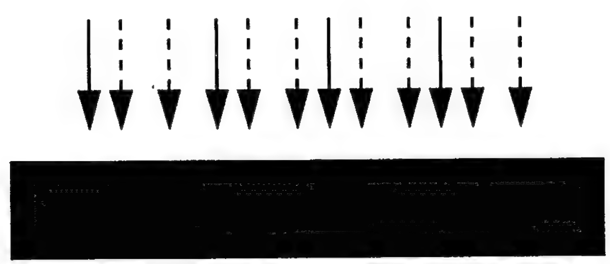
- Beyond Optical Lithography:Large Technology Change
- Beyond Industry Focus (>6 years)
- New Novel Approaches Possible

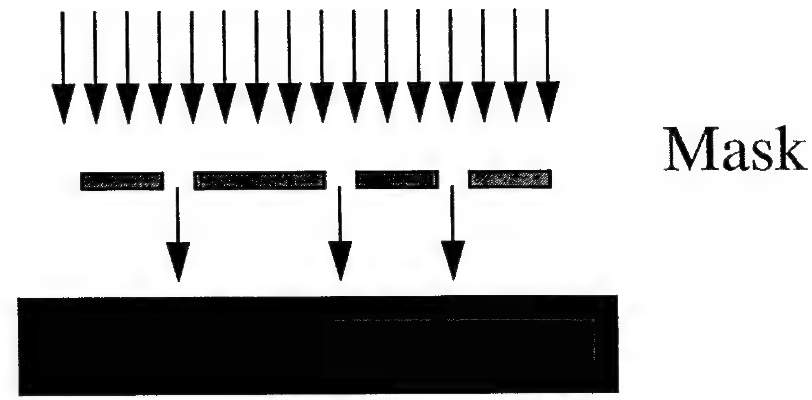
Typical Lithography Scenario

- Wafer Size: 300 mm diameter
- Chip Size: 30mm x 30mm
- Minimum Feature: 100 nm
- Pixels Per Minimum Feature: 4 x4=16
- Pixels Per Chip:1.44 x 10^{12}
- Pixels Per Wafer: 1.08 x 10^{14}
- Throughput Required: 60 wafers/hour (or 1/60 wafer/second)
- Required Pixels/sec: 1.8 x 10^{12}

Maskless versus Mask Based Lithography

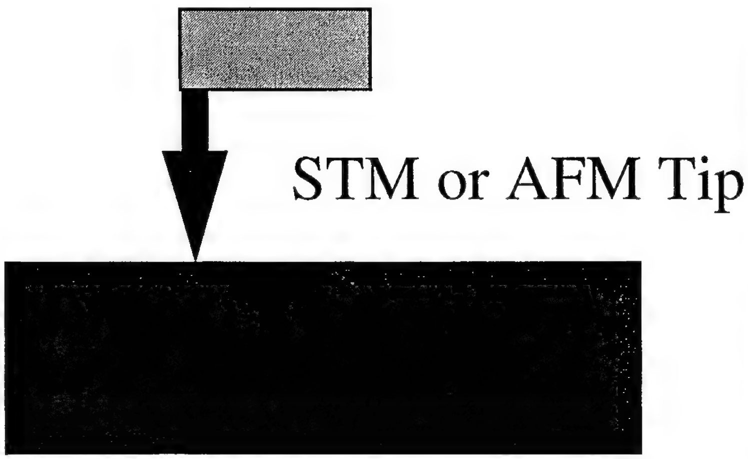
Address Individual Pixels

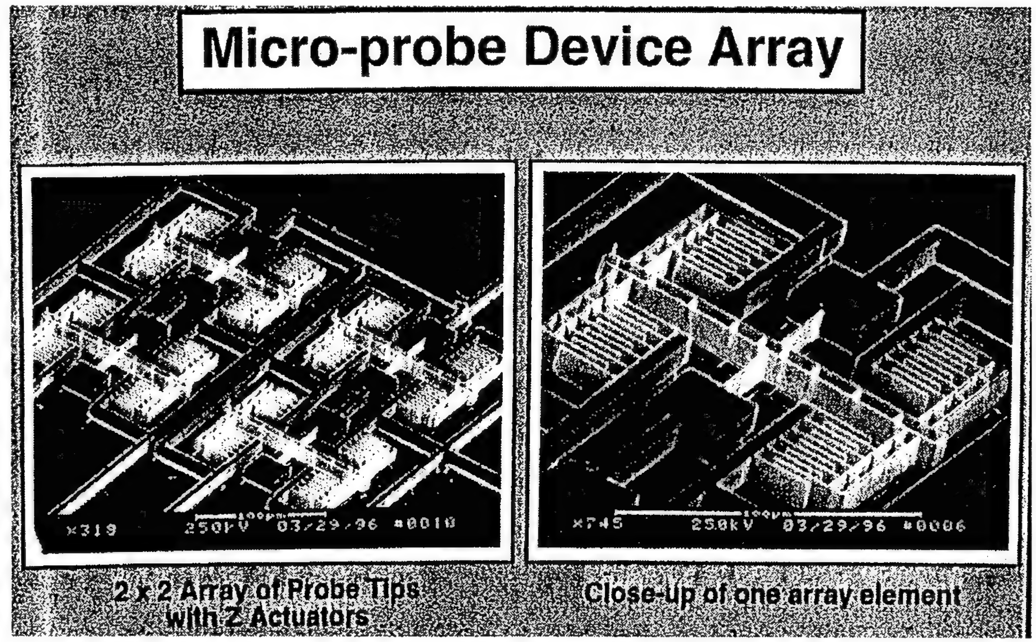




- Mask Based Lithography
  - Addressable Source
- Maskless Lithography
  - Simple Source
  - Need Mask

Proximal Probe Lithography

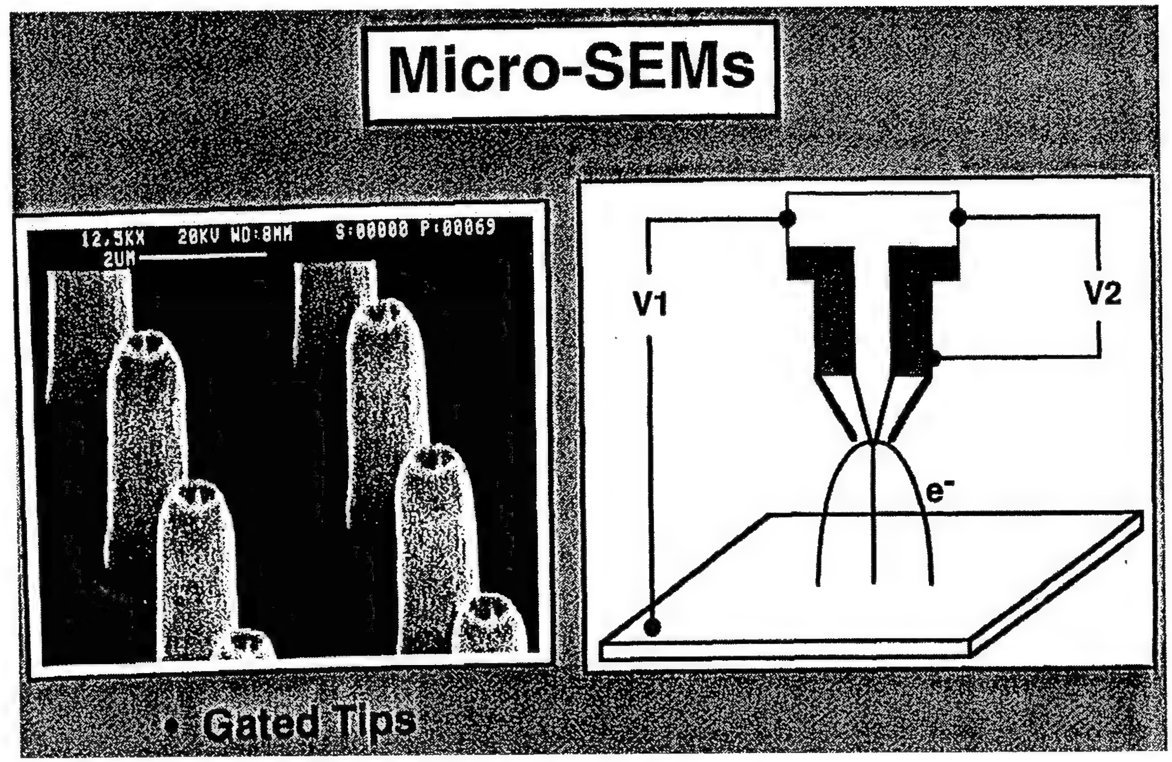




- Use Interaction Between Probe and Substrate to Write
- Make Lots of Individually Controlled Tips Using MEM's Techniques

Multiple E-Beams

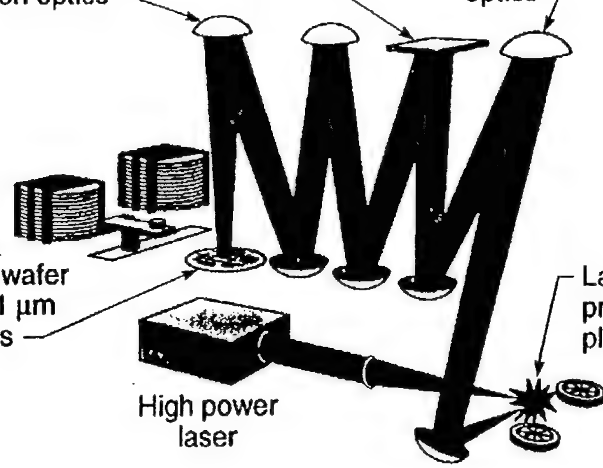
- Make Lots of Parallel E-Beams that Can Be Individually Programed
- MEM's Technology Major Enabler



Extreme Ultra-Violet

An evolutionary path beyond "deep-UV" lithography

EUV Lithography Stepper Concept



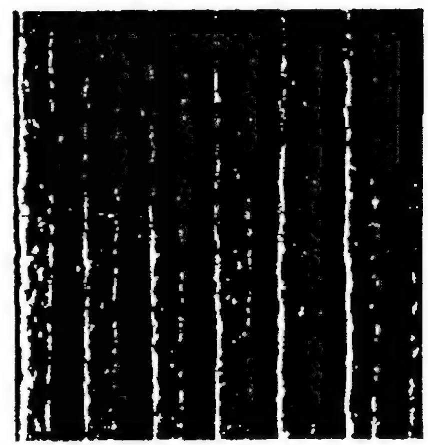
- 1 Gbit generation and beyond
  0.1 μm features → 0.05 μm features
- Logical extension of optical lithography
- Compact stepper

Critical Issues

- Multilayer reflection coatings
- Diffraction limited large-field optics
- Mask technology
- Source brightness
- Photoresist process

Experimental Results

0.075 μm lines & spaces



AT&T

Printing and Embossing Approaches

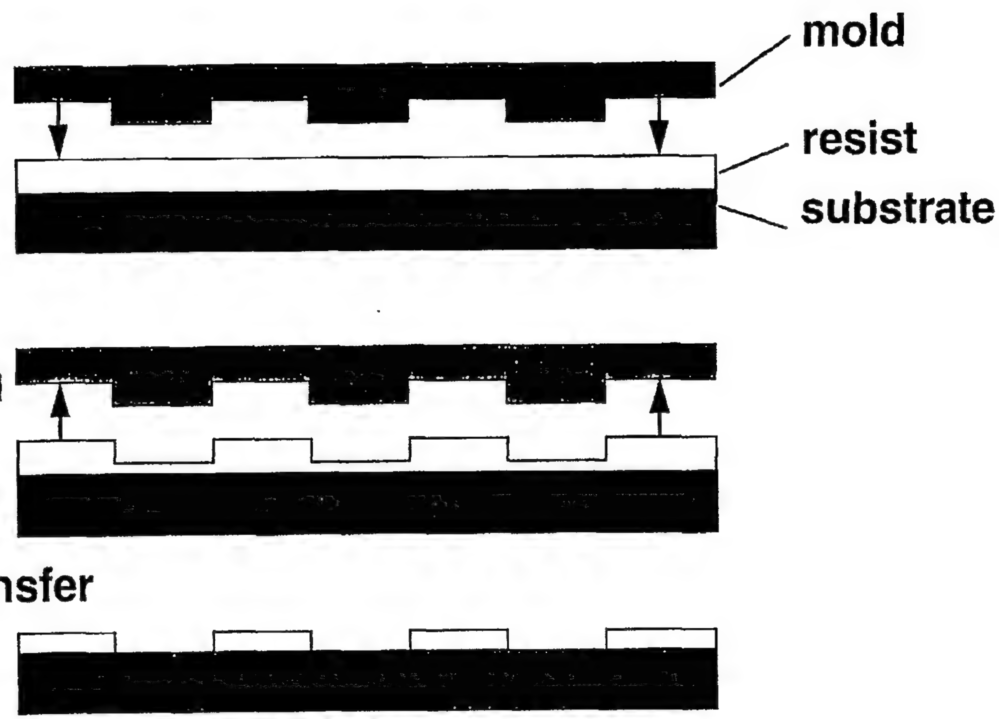
Nanoimprint Lithography

1. Imprint

•Press Mold

•Remove Mold

2. Pattern Transfer



Chou, Krauss, and Renstrom, APL, Vol. 67, 3114 (1995); Science, Vol. 272, 85 (1996)

NanoStructure Lab
UNIVERSITY OF MINNESOTA

Scientific and Technical Summary

- It is highly likely that conventional optical lithography will carry the semiconductor patterning load for the next 7 to 10 years, down to feature sizes of 130 nm to 100 nm.
- There are a number of contenders to follow optical for mainstream lithography, such as Extreme UV, Cell Projection E-beam, Ion Projection Lithography, 1X Proximity X-ray, SCALPEL, and so on.
- A major change in lithography technology is needed in the next decade, and new lithographic methods need to be explored, including maskless lithography.
- Lithography techniques capable of producing 25-30 nm structures will be required for "ultra devices".
- A key theme of the workshop was the required information content and data transfer rate in any future lithography technique.
- Chip sizes will increase and feature sizes will decrease, but also tolerances are shrinking.

Scientific and Technical Summary

- The requirement for arbitrary placement of 100 nm features on a 300 mm wafer requires over 10^{14} pixels per wafer. The standard for throughput is 60 wafers per hour, requiring a pixel data rate of over 10^{12} Hz.
- Any pixel-based lithography scheme, whether optical, e-beam, scanning probe, or whatever, is subject to this data rate issue.
- Specific technologies considered in the workshop were:
  - Maskless
    - Scanning probe lithography,(STM)
    - MEMs-based multiple e-beam lithography
    - MEMs-based optical lithography
  - Masked
    - Extreme UV lithography
    - Nanoimprint lithography
    - Self-assembling lithography

Scientific and Technical Summary

- Scanning probe lithography has extremely high resolution, at the atomic scale, but pattern transfer and low throughput are key issues. But scanning probe lithography may be viable for special applications.
- MEMs-based massively parallel e-beam lithography continues to show interesting potential for mainstream sub-100 nm patterning. Excellent progress has been made in the microactuators needed for scanning the multiple e-beam emitters. The key challenge in this approach is the development of suitable e-beam emitters.
- MEMs-based optical lithography, fashioned around the digital micromirror devices developed at Texas Instruments, is another maskless approach. Resolution beyond 100 nm and overall system data rates are still major concerns.
- Extreme UV lithography progress has been outstanding to date, and many of the fundamental feasibility questions have been answered. There are a lot of challenges remaining in the areas of defects, precision optics, and photon sources. It is yet to be demonstrated that a technically and economically viable lithography system can be developed for 100 nm patterning.

Scientific and Technical Summary

- Nanoimprint lithography is a novel patterning approach based on the ancient process of embossing. Nanometer scale resolution and pattern precision have been. At the very least nanoimprinting technology should be useful for single-layer patterns.
- Self-assembly is an interesting concept in that somehow the patterning structures "know" how to arrange themselves on a substrate. There have been a number of interesting demonstrations, and the key challenge for semiconductor applications is to create a technology that produces exactly the desired patterns and structures. A potentially useful role for self-assembly would be to create a reference structure for resists, substrates, thin films, or other elements of semiconductor chips.

Advanced Lithography

Workshop Organizers: T. McGill and G. Fuller

July 23, 1996

8:00 a.m.	**Introduction** Zach Lemnios and Dave Patterson (DARPA), Tom McGill (DSRC/CalTech)
8:30 a.m.	**Perspectives on Lithography** Fabian Pease (Stanford)
9:15 a.m.	**MEMS -Based Multiple Electron Beam Approaches to Lithography** Noel McDonald (Cornel)
10:00 a.m.	**Break**
10:30 a.m.	**Maskless Lithography Based on Digital Video Microdevices** Speaker TBD (TI)
11:15 a.m.	**STM-Based Lithography** Joseph Lyding (University of Illinois)
Noon	**Lunch**
1:00 p.m.	**Alternative Lithographic Approach** Steve Chou (University of Minnesota)
1:45 p.m.	**Self-Assemblying Lithography** George Whitesides (DSRC/Harvard)
2:00 p.m.	**Discussion**
4:00 p.m.	**Adjourn**

ADVANCED LITHOGRAPHY

JULY 23, 1996

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MASSIVE MEMORY TECHNOLOGIES

T. McGill

EXECUTIVE SUMMARY

Objective

Massive memories are a key component of modern information processing systems. The growth in capacity of these systems has been one of the major enabling technologies of the information revolution. High performance digital signal processing and computation systems need rapid access to large quantities of data. The major parameters characterizing a memory system include:

- Cost per unit storage
- Data transfer rates and seek times
- Weight
- Power Consumption

DoD Relevance

The DoD has some of the most demanding requirements for data storage systems. Modern digital battlefield requires the timely delivery of information from a large number of intelligence assets to the modern war fighter. Recent experiences in Vietnam and Desert Storm have highlighted the major failure of our intelligence assets to deliver accurate information to the warfighter in a timely manner. The antiquated film based storage of large amounts of imaginary makes it difficult to transmit rapidly, hard to analyze electronically and generally lowers its overall usefulness. Our very impressive overhead assets coupled with new Unmanned Autonomous Vehicles (UAVs) soon to be supplemented by even smaller and personal UAV's means that we will require very advanced memory systems to make effective use of these new assets. Terrabyte information systems will be carried by each individual soldier. To see how these systems might be used we have attached a table of what a terrabyte information system would enable.

Table 1. What would a TByte memory system enable.

Item	**Amount**
Standard TV	74 hours
HDTV	22 hours
100 Gbs Data Stream	80 sec
Terrain with resolution	62 sq mi
of 0.5 in (8 bit)	(7.89 x 7.89 mi)

Scientific and Technological Summary

For most applications cost of storage is traded off against the availability of the data. Random access systems (SRAM, DRAM, harddisk CD-ROM) generally are characterized by very small seek times in contrast to various tape media which require large seek times for non-contiguous data reads and writes.

The currently projected cost versus time for a number of systems show that memory technologies will continue to get less expensive for a given size. Dynamic random access memories (DRAMs) and static random access memories (SRAMs) are both following the 30% per year curves characteristic of the semiconductor industry. Hard disk drives are now following a 60% per year curve.

Traditional Memory Technologies Face Limits

Yet both of are facing potential limitations in the early part of the next decade. Hard disk drives will be limited by the so called superparamagnetic limit at roughly 10^x bits/cm^2. This limit will be reached in the year 2005 and will result in either a change in the approach or saturation in the cost for fixed capacity. Semiconductor memories are subject to scaling limits of transistors. DRAMs have the additional constraint of scaling in the capacitance that acts at the memory element.

New Memory Technologies

The saturation in these traditional memory technologies opens up the possibilities for new memories. These include:

- Semiconductor-Novel Memories Based on Nanostructures
- Hard Disks-New Magnetic Structures Not Subject to Superparamagnetic Limit
- Optical Memories
- Memories Based on Proximal Probes
- Polymeric Optical Memories Based on DNA Polymer

Optical Memories

Optical memories are becoming more important. The CD-ROM is entering a new era with DVD multilayers are likely Multi-Gbytes densities. Holographic memories are beginning to reach the product stage. However they have a relatively narrow window to reach the market place and become a serious competitor. Holographic memories need developments in materials both for inexpensive, polymer based products; and materials for master disk.

Proximal Probe Memories

Memories based on proximal probes show could reach very large densities 1.5×10^{15} Bits/cm^2. While there are important issues on how to write, read rates with new optical techniques are reaching 10 MBytes/sec, near rates for disk.

Summary

Until around 2005, memory is likely to continue to decrease rapidly in cost per unit storage (hard disk at 60%/year; semiconductor memories at 30%/year). Static random access memories will increase in speed with speed of circuits. However, dynamic random access memories and hard disks will not improve their transfer rates dramatically. There are opportunities for new memory technologies in the 10 year time frame. These include: nanostructure semiconductor memories;

optical memories; new magnetic structures; proximal probe memories and DNA polymer memories. There will be a major DoD need for massive memories to support high data rate sensors. US industry is not making adequate investments.

Suggestions for DARPA Action

- Invest in basic materials program both for masters and copies for holographic optical memories.
- Invest in basic research programs for: new high density/high performance semiconductor memories; new magnetic structures for memories beyond supreparamagnetic limit; proximal probe memories for the highest density; and polymer based optical memories.

Electronics for DoD

Discussion Group

David Ferry

Barry Gilbert

Zach Lemnios

Carver Mead

Tom McGill

Norm Ortwein

Bill Oldham

Fabian Pease

Gernot Pomrenke

Rafel Reif

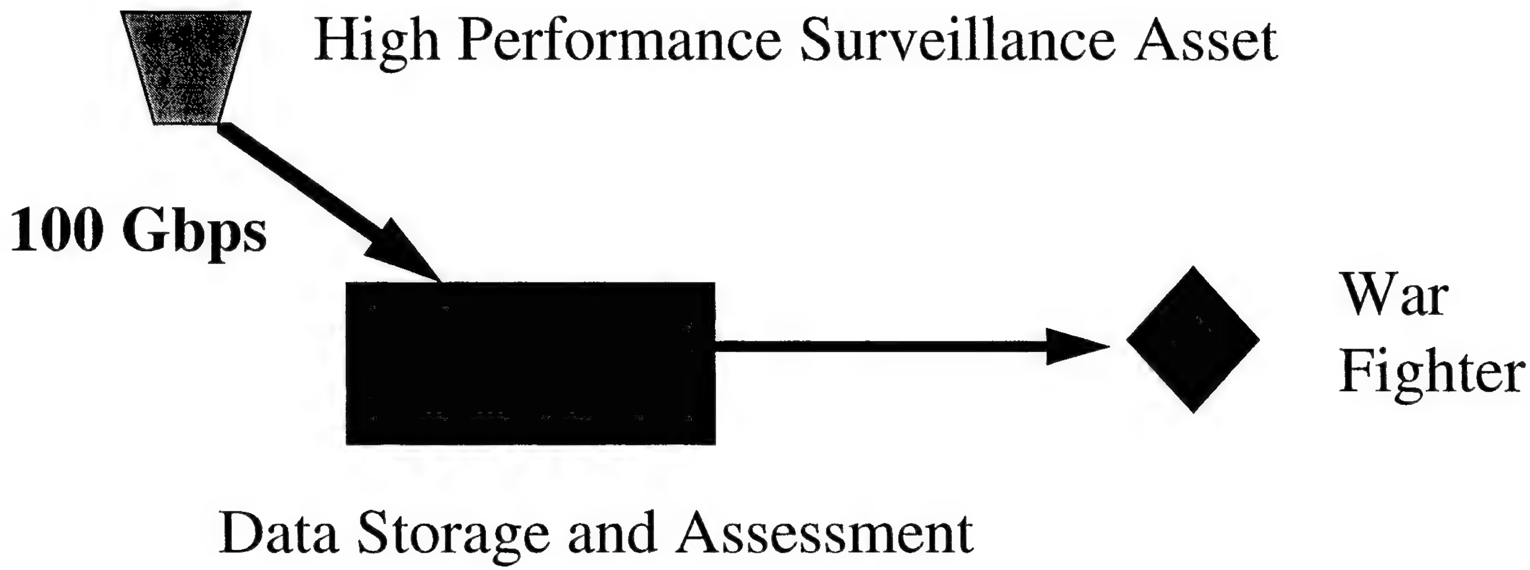
US Electronics Industry

- Very Successful
- Very Conservative
- Very Near Term r&D programs (< 6years)
- High Risk Aversion
- Avoid New Product Risks
  - Concentrate on Proven Products
  - Do Not Deviate from Seriously Successful Product Development Trends
  - Cost-Constrained, Increments rather than Highest Performance

DoD

- Need to Insure Dominance in Electronics because of its Importance as a Force Multiplier in the US Strategy
- High Performance Systems
  - Massive Memories
  - High Speed Digital Signal Processors-Verge of a Revolution in all-digital Radars, EW, and Communications based on Recent Breakthroughs in High Speed A/D Devices and D/A Converters
- Smart Sensors/Actuators
  - Pixel Based Image Processing
  - Auditory
  - "Smart Nose"
  - Multi-Spectral Imagers
  - MEMs Based Actuators

Advanced DoD Systems



- Need High Performance Electronics
- High Performance Data Links
- Lots of Storage

DoD Application

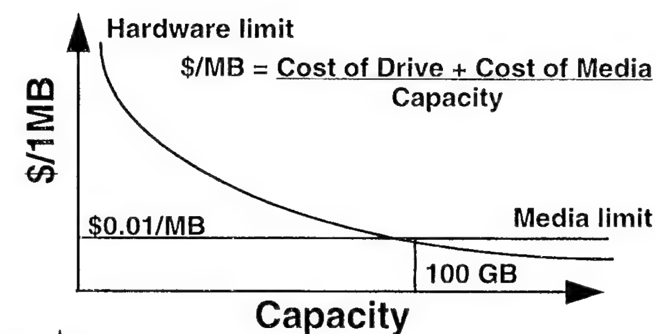
Item	Amount in 1 TByte
Standard TV	74 hours
HDTV	22 hours
100 Gbs Data Stream	80 sec
Terrain with Resolution of 0.5in(8bits)	62 sq mi (7.89 mi by 7.89 mi)

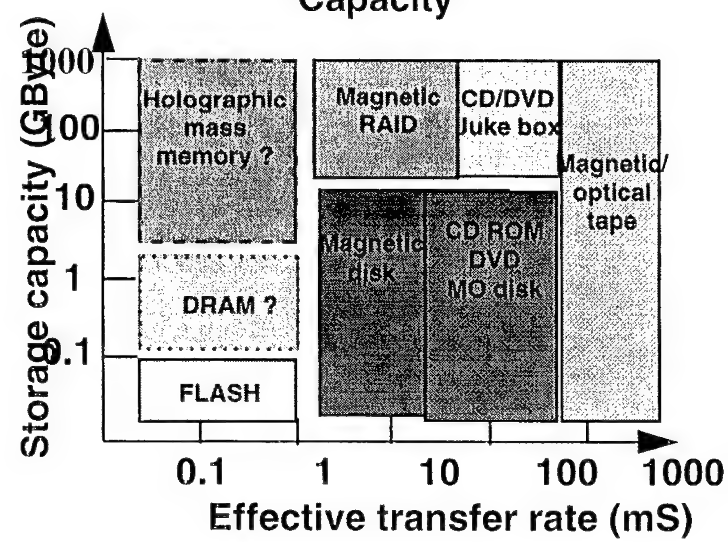
- Tbyte Storage Required for Many of the Future DoD Missions

Massive Memory

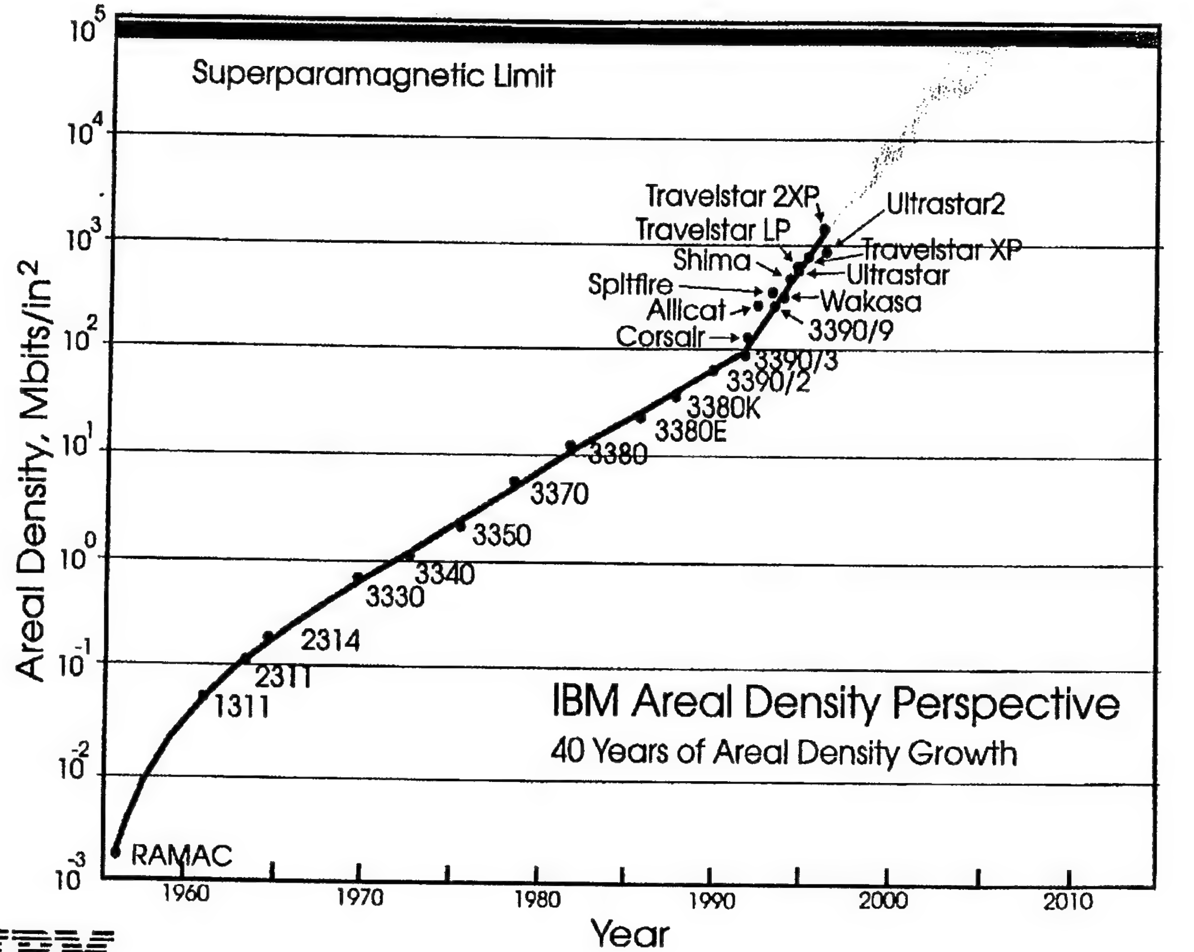
Trends in memory devices:

- ❑ Cost per stored megabyte
  - ■ Cost of magnetic media $0.16 to $0.10 per Mbyte
  - ■ Cost of MO and CD-R media $0.16 to $0.10 per Mbyte
- ❑ Effective Data Transfer Rate
  - ■ Access time and data rates
- ❑ Removable media
  - ■ Physical Transport





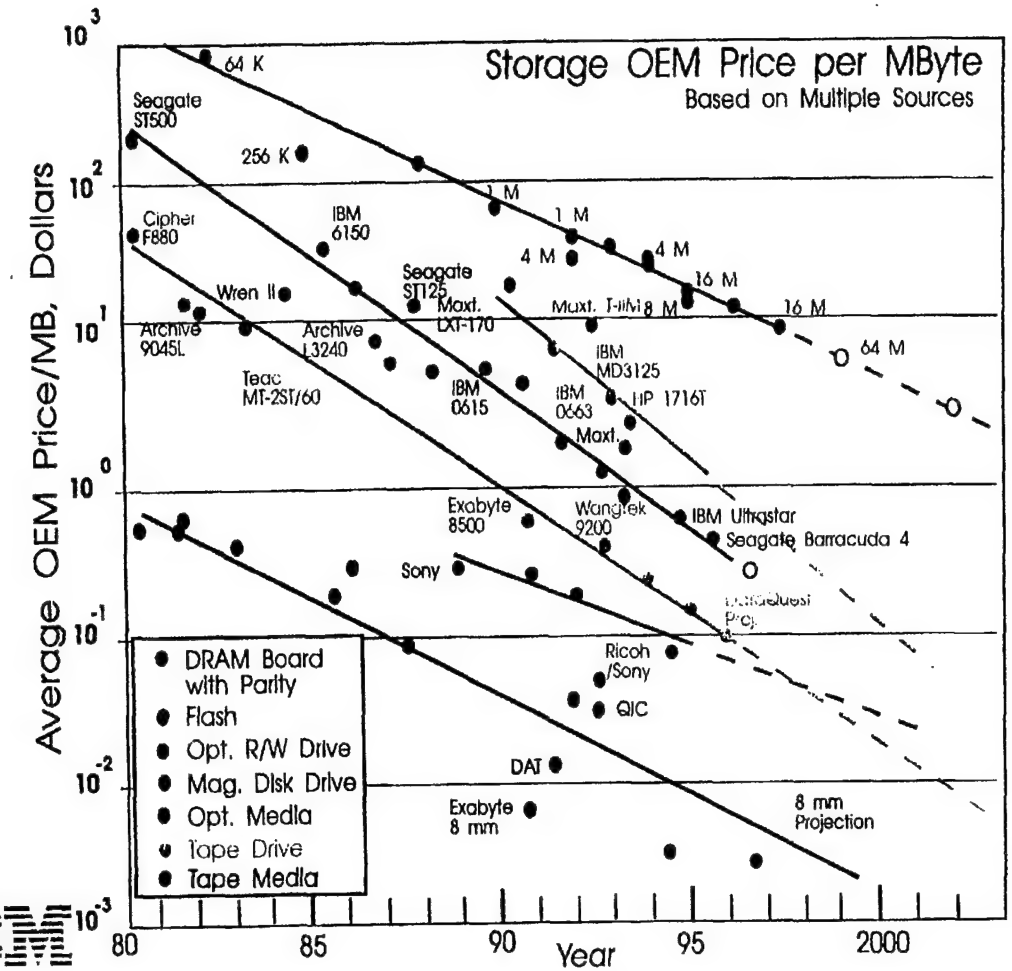
Rapid Evolution of Memory (Hard Disk)



IBM Advanced Technology

Fundamental Physical Limit

Technology Cost Versus Time



All of the Memory Technologies are Evolving Rapidly

Traditional Memory Technologies Face Limits

- Semiconductor Memory
  - Subject to Limit on Scaling for Transistors
  - Possible Limitations on DRAM Capacitance could Limit its Evolution
- Magnetic Hard Disk
  - Faced with Superparamagnetic Limit around 2005
- Magnetic Tape Still Involving But Not Random Access

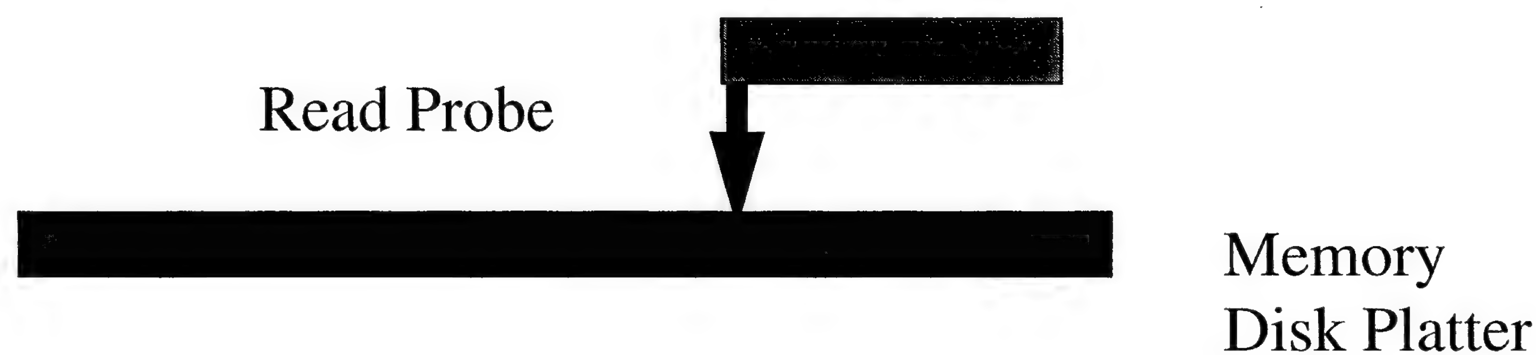
New Memory Technologies

- Semiconductor-Novel Memories Based on Nanostructures
- Hard Disks-New Magnetic Structures Not Subject to Superparamagnetic Limit
- Optical Memories
- Memories Based on Proximal Probes
- Polymeric Optical Memories Based on DNA Polymer

Optical Memories

- CD-ROM Entering a New Era with DVD Standard and Multilayers (Densities at Multi-Gbytes Likely)
- Holographic Memories Need Product
  - Need Materials both for Inexpensive, Polymer Based Products; and Materials for Masters
  - First Products Just Appearing

Proximal Probe Memories



- Density could be Very Large at Limit (1.5×10^{15} Bits/cm^2)
- Read Rates with New Optical Techniques ~10 MBytes/sec (Near Disk Rates)

Summary (1)

- Memory are likely to continue to decrease rapidly in cost per unit storage (Disk at 60%/year; Semiconductor at 30%/year) Until Around 2005
- Static Random Access Memories will increase in speed with speed of circuits
- Dynamic Random Access Memories and Hard Disks will not Improve Transfer Rates Dramatically

Summary (2)

- Opportunities for New Memory Technologies in the 10 year time frame
  - Nanostructure Semiconductor Memories
  - Optical Memories
  - New Magnetic Structures
  - Proximal Probe Memories
  - DNA Polymer Memories
- Major need for DoD with High Data Rate Sensors
- US Industry Not Making Adequate Investments

Suggestions for DARPA Action

- Invest in Basic Materials Program both for Masters and Copies for Holographic Optical Memories
- Invest in Basic Research Programs for:
  - New Semiconductor Memories, High Density/High Performance
  - New Magnetic Structures for Memories Beyond Supreparamagnetic Limit
  - Proximal Probe Memories for the Highest Density
  - Polymer Based Optical Memories

Massive Memory

Workshop Organizer: T. McGill

July 24, 1996

8:00 a.m.	**Introduction** Zach Lemnios and Gernot Pomrenke (DARPA), Tom McGill (DSRC/CalTech)
8:30 a.m.	**Optical Massive Memories** Demetri Psaltis (Caltech)
9:30 a.m.	**Magnetic Approaches for Massive Memories** John Best (IBM Almaden)
10:30 a.m.	**Break**
11:00 a.m.	**New Magnetic Devices and Massive Memories** Steven Chou (University of Minnesota)
11:30 a.m.	**Proximal Probe-Based Memories** K. Wickramasinghe (IBM Watson)
Noon	**Lunch**
1:00 p.m.	**STM-Based Massive Memories** TBD
1:30 p.m.	**Semiconductor-Based Mass Memories** Harold Levy (VLSI Research)
2:00 p.m.	**Discussion**
3:30 p.m.	**Adjourn**

Massive Memory

July 24, 1996

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NEW MATERIALS FOR ACTIVE OPTICAL CIRCUITS

R. Osgood, D. Miller, E. Hu, M. Beasley, DSRC

R. Leheny, A. Husain, DARPA

EXECUTIVE SUMMARY

Objective

Examine the technology limiters for incorporation of more extensive functionality in integrated optoelectronic chips.

DoD Relevance

Functional integration has been a proven method of reducing the cost of digital, analog, and microwave systems for Defense applications. Recently the same approach has begun to examined for the case of optical circuits. These integrated optical chips have been used for a variety of communication and RF applications, including those for RF sensing and phased-array radar. However the materials needed for truly large-scale implementation of these circuits has only begun and further progress in this area will require several important developments in materials technology. The scale of the work in this area is much beyond that accessible to the single principal investigator–requiring the involvement of circuit designers, materials researchers, and device engineers.

Summary of the Scientific and Technical Issues

The Workshop included a broad range of materials technology which is being considered and, in some cases, even used for various forms of photonic integrated circuits. In addition, in several cases the materials issues were brought into sharper focus by presentations of existing applications of these circuits. These application drivers included multiple delay lines and switches for optically controlled phased-array radar, high-speed linear modulators for RF sensing and antenna remoting, WDM components for high speed data communication. In addition, the emerging role of optics in computer communication was briefly discussed. More extensive discussion of these applications was presented the next day in an-depth Workshop organized by David Miller on the following day.

Progress and needed developments in each of the materials technology were discussed extensively. A summary of these discussions is included at the end of this Executive Summary. Basically however several of the materials systems were very mature and thus had an impressive series of materials performance data in hand as well as work directed toward specific applications. These more mature technologies included $Si0_2$ on silicon which has very high optical transmission and easy of fabrication, $LiNbO_3$ which also has excellent loss characteristics as well very-high-speed modulation rates, and finally III-V semiconductors which are highly functional and capable of excellent performance. On the other even these "mature" materials had important requirements for further R&D. For example in the case of $LiNbO_3$, there are several reasons to have the capability of epitaxial growth of thin films. Specifically, such growth would make it

make it possible to form more strongly confining waveguides as well as to allow low-threshold "on-chip" laser sources. In SiO_2 the need is to develop more functionally through the incorporation of rare-earth-dopant ions.

Other materials had achieved some impressive results but were still in early form of development. An excellent example was the case of small-molecule organics and polymers. In the case of the later, excellent passive waveguide strictures have been demonstrated and in fact are used in multimode mode computer interconnects. However, the lifetime for active polymeric materials is still not sufficiently long to still allow them entry into the commercial market. In the case of the small-molecule systems, very high quality displays have been demonstrated however their lifetime is still not sufficiently long. In these promising systems clearly several areas of research need attention.

Finally in two cases the research is promising but still at an even stage of developments. Thus for Si optical circuits there is still much work to be done on making efficient light emitters, although Er doping has been successfully demonstrated and implemented in an on-chip communication circuit. In the case of tungsten-bronze materials, research is still at the stage where it is important to develop the basic waveguiding system. However this technology has the important advantages of relatively low modulation voltage and the capability of heterogrowth of PZT layers.

Conclusions

The detailed comparative conclusions of the Workshop are contained in the summary table included with this report. In addition, several more extensive comments can be made as follows:

1) The materials system with the highest combination of performance and functionality are those based on combinations of III-V semiconductors. Circuits made from these materials have demonstrated all of the most essential capabilities for fully functional use. Further these demonstrations have been done at high levels of performance and for relatively "beginner" commercial applications. The central issue with this materials system is to lower costs to the point where some market driver will help improve manufacturing efficiencies. Currently this application appears to be that of some form of high bit rate telecommunications. Other than cost the next most significant problem is reliably obtaining high growth uniformity.

2) A reoccurring theme with the discussions of oxide-based materials was the need for some form of thin-film epitaxial growth. This would allow for the growth of higher-confinement waveguide structures as well as more efficient lasers. In addition, thin-film growth of oxides is needed in other applications of electronic materials as well. It is clear that a serous program to explore new epitaxial growth methods for these materials would be most desirable.

Note that despite its limited "active" device functionality, $LiNbO_3$ continues to be the material of choice for several critical areas of optics in RF systems and fiber optic gyros.

3) Organics materials are the clear choice for very large-area photonic circuits for large-area arrays of interconnects. The central issue for greater adoption of organics is to achieve active functionally with long device lifetime. It is believed that this capability may be achieved within the near future. The small-molecule version of the organic family appears to be an excellent choice for low-cost displays.

4) The overall conclusion is that even in their present early stages active optical circuits have played an important role in making several advanced optical systems progress through early development; in some cases these circuits have become commercial products. Expansion of their functionality should lead to continued realization of advanced communication, radar, and sensing systems.

Observations

The final observations of this Workshop are very much in accord with those in the Workshop on Materials Interfaces for Electronic and Optoelectronic Materials.

1) Progress in O/E materials processing and functionality will continue to be a major enabler for new integrated systems which are DoD specific.

2) The progress on various materials integration technology as well as the DoD need in fully integrated mixed technology systems makes it clear that the time is appropriate to develop demonstration modules which address key DoD missions.

NEW ACTIVE OPTICAL MATERIALS SUMMARY CHART

Material System	Pro	Con	Breakthroughs Needed	Application (Largest)
III–IV	• Performance	• Cost	• Materials control • Large market	• Communication
Si	• "Rides" Si IC technology	• Performance of emitter	• Modulator/better emitter	• Data communication
$LiNbO_3$	• Performance • Cost	• Low integration density • Packaging	• Homoepitaxy	• Microwave/photonics
Other Oxide Crystals	• Unusual functionality • Low Voltage	• No commercial base method • Processing technology	• Low loss waveguide	• Fiber sensing
Polymers	• Low cost • Integrability	Lifetime (Active material)	• Thermal stability	• Phased array radar
Small molecule organics	• Low cost • Emitter	• Lifetime • Processing	• Thin film technology	• Heads up displays
SiO_2-based	• Passive devices are here!	• No active capability	• Multifunction	• Phased-array radar

New Materials for Active Optical Circuits

Workshop Organizer: R. Osgood

July 25, 1996

8:00 a.m.	**Opening Remarks** Bob Leheny, Anis Husain (DARPA), Rick Osgood (DSRC/Columbia)
8:15 a.m.	**Active Semiconductor Circuits: Applications and Future Technology** Tom Koch (SDL)
9:00 a.m.	**The Role of Silicon in Active Components for Optical Circuits** Lionel Kimmerling (MIT)
9:45 a.m.	**Break**
10:15 a.m.	**Active Components for Integrated SiO_2** John MacChesney (Lucent)
11:00 a.m.	**Active Polymers for Integrated Circuits (and Displays)** Steven Forrest (Princeton University)
11:45 a.m.	**Lunch**
1:00 p.m.	**$LiNbO_3$ Technology: Optical Circuits for Defense Applications** Fred Leonberger (Uniphase Telecommunications Products)
1:30 p.m.	**$LiNbO_3$ Technology: Active $LiNbO_3$ Devices** Leon McCaughan (University of Wisconsin)
2:00 p.m.	**Other Crystalline Materials** Henry Taylor (Texas A & M)
2:45 p.m.	**High Speed Optical Modulators in Polymers** Geoffrey Lindsay (U.S. Navy, Chemistry & Materials Branch)
3:15 p.m.	**General Discussion**
4:15 p.m.	**Adjourn**

New Materials for Active Optical Circuits

July 25,1996

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FUTURE OF OPTICS IN DOD: OPTICS IN INFORMATION SENSING, COMMUNICATIONS NETWORKS, AND PROCESSING

D. Miller, R. Osgood

EXECUTIVE SUMMARY

Objective

To identify the driving applications for optics now, and in the future, in sensing, communications networks, and information processing, and to assess the directions optical systems, technology, and science should therefore take.

DoD Relevance

Optics is applicable in many DoD systems related to information, from sensing, through communications, to processing. In addition to extensive use in imaging, and novel sensing possibilities, optics has the potential to reduce size, power, weight, and cost, to enable handling of very high information bandwidths (e.g., for battlefield awareness), and to deliver multifunctional systems.

Summary of Scientific and Technical Issues

This workshop looked at the applications of optics in information for DoD in the areas of sensing, communication, and information processing. Optics will be important in many such DoD applications, especially because of its ability to sense and handle very large information rates.

The workshop featured talks by Dennis Killinger (University of South Florida) ("DoD Lidar Applications and Optical Remote Sensing of Chemical Species"), Patrick Trotta (Texas Instruments) ("Trends in Sensors and Sensor Optics"), Mike Wechsberg (Hughes) ("RF Optoelectronics"), Vincent Chan (Lincoln Labs) ("Global Defense Network"), Mike Ebsen (Computing Devices International) ("Role of Optics on Next Generation Platforms"), and Craig Lund (Mercury Computer Systems Inc.) ("Optics in Embedded Processors").

Systems and applications that optics can impact include

- remote sensing (e.g., laser radar, detecting exhaust clouds and trails, detecting chemical warfare agents, mapping chemical clouds, search and track),
- imaging (e.g., low-light-level/night/enhanced vision, autonomous and standoff systems)
- optically controlled radio frequency antennas (e.g., for antenna remoting, multiband satellite communications, wideband steerable jammers, wideband foliage-penetrating synthetic aperture radar, protected communications with agile beams),
- very high bandwidth communications (e.g., sensor information processing, very-high-capacity networks and optically-assisted switching systems),
- high performance and/or embedded processors (e.g., for programs such as JSTARS (Joint Surveillance Target Attack Radar System), Foothill EIS-HYB, ASCI White).

(Optics also is useful for displays and information storage, and in weapons, countermeasures, range-finding and target designation, though these are beyond the scope of this report.)

Applications demand systems with

- lower cost
- lower power, size, and weight, allowing deployment on mobile, airborne, or satellite platforms
- larger information handling capacity, e.g., from image sensors
- more sophisticated sensing functionality, including, e.g., multispectral, chemically specific detection, enhanced night vision, hyperspectral detection (multispectral imaging)

There are many scientific reasons now well understood as to why optics can help achieve these demands of DoD systems. Basic science and technology are continuing to establish new reasons and refine existing ones. DARPA has been very effective in advancing optical and optoelectronic science, device technologies, and system concept demonstrations that make many of the opportunities for exploiting optics possible.

The problem of taking advantage of currently understood optical and optoelectronic principles often lies now not in the devices or materials considered in isolation, but in the ability to integrate diverse devices or materials into compact, high-performance systems that can conform to the constraints of the applications. A key technical theme that emerges to allow us to take more advantage of optics in such applications is *"heterogeneous integration"*, including

- integrating disparate materials to allow engineering of new material functionality (e.g., custom nonlinear optical materials) and provide the basis for other integrations (e.g., electronics to optoelectronics, optoelectronics to optics, optics to mechanics)
- integrating optoelectronics in larger numbers (e.g., arrays of lasers, photodetectors, and modulators)
- integrating enhanced functionality into or with optoelectronics (e.g., multispectral detection, integration with electronics for amplification and local sensor information processing)
- packaging optoelectronics with optics (e.g., fibers, multiwavelength optical components, integrated waveguides and/or microlenses)
- packaging optics with mechanics (e.g., conformal optics to reduce drag and electronic signature, optical array connectors, lightweight high-density optical backplane assemblies)

The main benefits of heterogeneous integration are those needed by systems, including

- reduced cost (e.g., more efficient manufacturing, reduced design cost through use of optical interconnects (eliminate electromagnetic design of high speed boards, eliminate noise problems of high performance electrical links), reduced programming cost by allowing interconnect network architectures more favorable to the system)
- reduced size (e.g., integrated arrays of devices, optical interconnections to fit STAP (space-time adaptive processing) embedded processors into the 6U form factor (paperback sized) required by the application)
- reduced weight (e.g., eliminate microwave "plumbing", heavy electrical cabling)

- reduced power dissipation (e.g., less high-power, long-distance electrical interconnections)
- improved processor scalability (e.g., advanced processor network topologies enabled by dense optical interconnection, allowing systems to exploit evolving silicon technology)
- enhanced functionality (e.g., active radar apertures, local digital signal processing, multiwavelength detectors)
- improved maintainability (e.g., hot swapping of optically interconnected processor boards, dynamic reconfigurability of processor networks)
- signature reduction (e.g., reduced visibility to radar, etc.)
- reduced electromagnetic interference (EMI) (e.g., from optical interconnects)
- improved ruggedness.

A specific example of a heterogeneous integrated system would be an optically interconnected embedded processor for an airborne platform. Optical interconnections would allow higher connector densities from multichip modules to the (optical) backplane, making the system physically smaller. Such higher densities would reduce the design problems encountered with high density electrical backplanes, and allow more highly connected networks to be implemented, thereby improving system performance, simplifying the programming by reducing network contention, and allowing scalability to larger numbers of processors. Such high density optical interconnects not only require arrays of optoelectronic devices (such as detectors and lasers or modulators), but also require, for example, (i) that the optoelectronics be efficiently integrated with electronics, (ii) that optics (e.g., waveguides) be integrated with the multichip module, (iii) that parallel optical connectors be available for module to board connection, (iv) that integrable optical "wiring" technology exists for the backplane.

Conclusions and Observations

Optics has very significant potential to improve the performance of sensing, communications, and information processing systems for DoD applications. This potential is not only for producing high performance *per se*, or for delivering functions (such as imaging) that can be performed no other way, but also for enabling systems to achieve the improved power, size, weight, and cost demanded by DoD applications. Optics, working with other technologies such as electronics, appears especially to have the key features necessary to allow information systems to continue to scale to higher information capacities (e.g., >1 Tb/s).

DARPA's role has been very important in advancing the science and technology that enables these optical opportunities. It is important, too, that it maintains this role in the future. In advancing to the next level of implementation in systems, DARPA's role is also very important, because DoD applications generally have demands (especially for size, power, weight, and information handling capacity) that significantly exceed commercial specifications.

Clearly, the advantages of optics are of no use if they cannot be exploited in real systems that can meet the special constraints of DoD applications. To this end, the main theme that emerged from the diverse areas considered in this workshop is *"heterogeneous integration"* - the ability to integrate efficiently, effectively, and at large enough scale, the diverse technologies required for the system.

Continued advances in optical science, devices, and specific technologies remain important and worthy of support, since many novel optical physical concepts and technologies with future revolutionary potential (e.g., ultrafast optics and optoelectronics) remain to be exploited. Such basic

work may be particularly effective for DoD if it includes serious examination of the ultimate impact on systems, or operates in the multidisciplinary areas that could impact the ability to use technologies together to make improved systems.

Future of Optics in DoD: Optics in Information–Sensing, Communications Networks, and Processing

David Miller and Richard Osgood

Objective

To identify the driving applications for optics now, and in the future, in sensing, communications networks and information processing and to assess the directions optical systems, technology, and science should therefore take.

DoD Relevance

Optics is applicable in many DoD systems related to information

sensing (including imaging)
communications
processing

Optics can

reduce size, power, weight, and volume
enable handling of very high information bandwidths
deliver multifunctional systems

Summary of Issues–Systems and Applications for Optics

- remote sensing (e.g., laser radar, detecting chemical clouds)
- imaging (e.g., low-light-level/night/enhanced vision, autonomous systems)
- optically controlled radio frequency antennas (e.g., for antenna remoting, multiband satellite communications, wideband steerable jammers, protected communications with agile beams)
- very high bandwidth communications (e.g., sensor information processing, very-high-capacity networks and optically-assisted switching systems)
- high performance and/or embedded processors (e.g., for JSTARS, Foothill EIS-HYB, ASCI White)

(Optics also is useful for displays and information storage, and in weapons, countermeasures, range-finding and target designation, though these are beyond the scope of this report.)

Summary of Issues– Applications Requirements on Systems

- lower cost
- lower power, size, and weight (e.g., for mobile, airborne, or satellite platforms)
- larger information handling capacity (e.g., from image sensors)
- more sophisticated sensing functionality

Summary of Issues– Key Theme "Heterogeneous Integration"

- **integrating different materials, devices, and technologies to address the applications requirements on systems, e.g.,**

  integrating disparate materials to allow engineering of new material functionality and provide the basis for other integrations

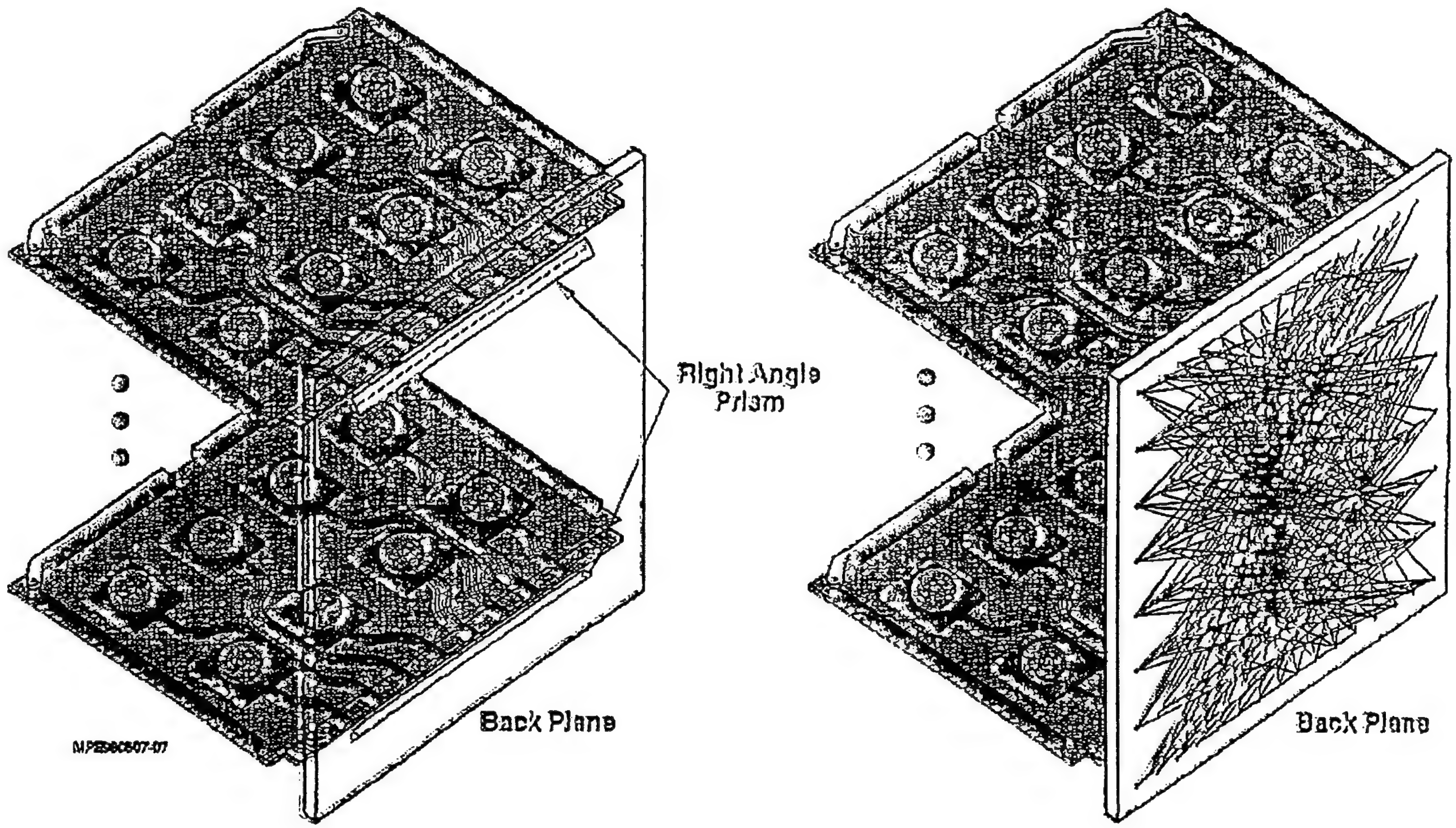
  integrating optoelectronics in larger numbers

  integrating enhanced functionality into or with optoelectronics

  packaging optoelectronics with optics

  packaging optics with mechanics

Backplane



Conclusions and Observations

- **Optics has very significant potential to improve the performance of sensing, communications, and information processing systems for DoD applications**

  delivering functions (such as imaging) that can be performed no other way

  reduce power, size, weight, and cost

  scale to higher information capacities (e.g., >1 Tb/s)

- **Field remains fertile at the basic level**

  multidisciplinary work and work addressing ultimate system impact particularly important for DoD

- **DARPA's support crucial because DoD applications exceed commercial specifications**

- **"Heterogeneous integration" very important theme**

  the ability to integrate efficiently, effectively, and at large enough scale, the diverse technologies required for the system

Future of Optics in Defense Systems

Workshop Organizer: D. Miller

July 26, 1996

8:00 a.m.	**DARPA Perspective** Anis Husain, Bob Leheny (DARPA)
8:30 a.m.	**DoD Lidar Applications and Optical Remote Sensing of Chemical Species** Dennis Killinger (University of South Florida)
9:15 a.m.	**Trends in Sensors and Sensor Optics** Patrick Trotta (Texas Instruments)
10:00 a.m.	**Break**
10:30 a.m.	**RF Optoelectronics Applications** Mike Wechsberg (Hughes Aircraft)
11:15 a.m.	**Global Defense Network** Vincent Chan (Lincoln Labs)
Noon	**Lunch**
1:00 p.m.	**Role of Optics on Next Generation Platforms** Mike Ebsen (Computing Devices International)
1:45 p.m.	**Optics in Embedded Processors** Craig Lund (Mercury Computer Systems, Inc)
2:30 p.m.	**Discussion**
4:00 p.m.	**Adjourn**

Future of Optics in Defense Systems

July 26, 1996

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COUNTER TERRORISM WORKSHOP (RUMP SESSION)

G. Kovacs (DSRC)
R. Dugan, J. Alexander (DARPA)

JULY 11, 1996

Defense

A List

1. Software for design of bases, identification of choke points, identification of bait areas, iden tification of crucial roads and portals, use for retrofit and new design, choke points.
2. Burn through explosives, low order detonation laser, H_20 jet, infrasonics, foams.
3. Chemical additives to nitrates to foil explosive creation or make noxious substances.
4. Acoustic blast "lightening rod."
5. Counter blast, solve timing issues.
6. Building reinforcement/retrofit with high-tech materials carbon fiber wrap for collapse prevention.
7. Inflatable blast protection, "air bag for a building," H_20 bladder, hard shield, sand-filled first floor, . . .

B List

1. Passive barriers, fences, walls, 8-ft. sunken roads.
2. EOD guy to every base (911 for explosives).
3. Beepers on building occupants, PA system in buildings.
4. Low-tech building reinforcement, dirt burns around buildings.

7/11/96 -> XAN'S TEAM
D = DARPA-LIKE

Detection At Portals
* move out the portals (simple)

D—sensors for particulates—explosive/high N cargo, vapors, fuel oil

Technology: portal air shower, chemical detector (sampling) dogs, swipes (outside of vehicle), test driver's hand (see below)

Vehicle too heavy/abornmal weight distribution -> scale in portal, can actively vibrate truck and look for resonant signatures

Wrong content of vehicle/modifications (false compartments)—laser ranging for internal vs. external dimensions, weight distribution on tires, chemical sensors

(GC, IMS, mass spec), x-ray

Nervous people—measure hand: blood pressure, galvanic, hand/fingerprint ID,

"Fear" sensors (constituents of sweat?), voice tremors wrong driver - hand ID, voice ID, retinal scan, iris scan

Bad ID/papers–transponder, smart chip for bill of lading

Dogs—could instrument them with GPS, transmitter, camera, trouble switch—they spot trouble and call in

High quality info/vetting of expected entries

Vehicle ID - transponder (obvious, difficult to remove), burglar alarm, license plate reader

Cross-correlation of information key!!!

Need ability to update security measures

Detection at Perimeter or Within Enclave

Perimeter needs to be moved out.

D—advanced, hierarchichal surveillance & interrogation

UAV patrolling perimeter

intelligent, wireless, distributed sensors (thermal, magnetic, acoustic, seismic, etc.) -> low cost, wireless, weatherproof

Hierarchical system key -> intelligently "wake-up" sensors and processing -> finally alert people

Foveating -> focus expensive, single-point sensors on "hot spots" automatically

Interrogation: send guard dogs/people, turn on cameras/audio

Key: system integration/adaptive processing - avoid false alarms (likely in city) - machine intelligence

Identify unusual vehicles

Identify unusual behavior - people fleeing/running - micropulse radar

Instrumented dogs within enclave

D—genetically engineered insects (e.g. "fruit flies") to tag explosives

Interrogate vehicle transponders

Satellite surveillance of vehicles/people around permiter (or UAV)

Cameras on perimeter - activate on motion, continuous

Magnetic/Doppler magnetometry @ perimeter

License plate reader

exploit the road-sensors/transponders— if off-road, clearly suspicious

airborne/other threats: RPG/TOW/LAW (SP?), large bomb near perimeter, bazooka,

mortar, UAV, suicide truck bomb

DSRC COUNTER-TERRORISM BRAINSTORMING SESSION

DSRC WORKSHOP 1996
July 11th, 1996

Organized by: Regina Dugan and Xan Alexander

THREAT SCENARIO CONSIDERED

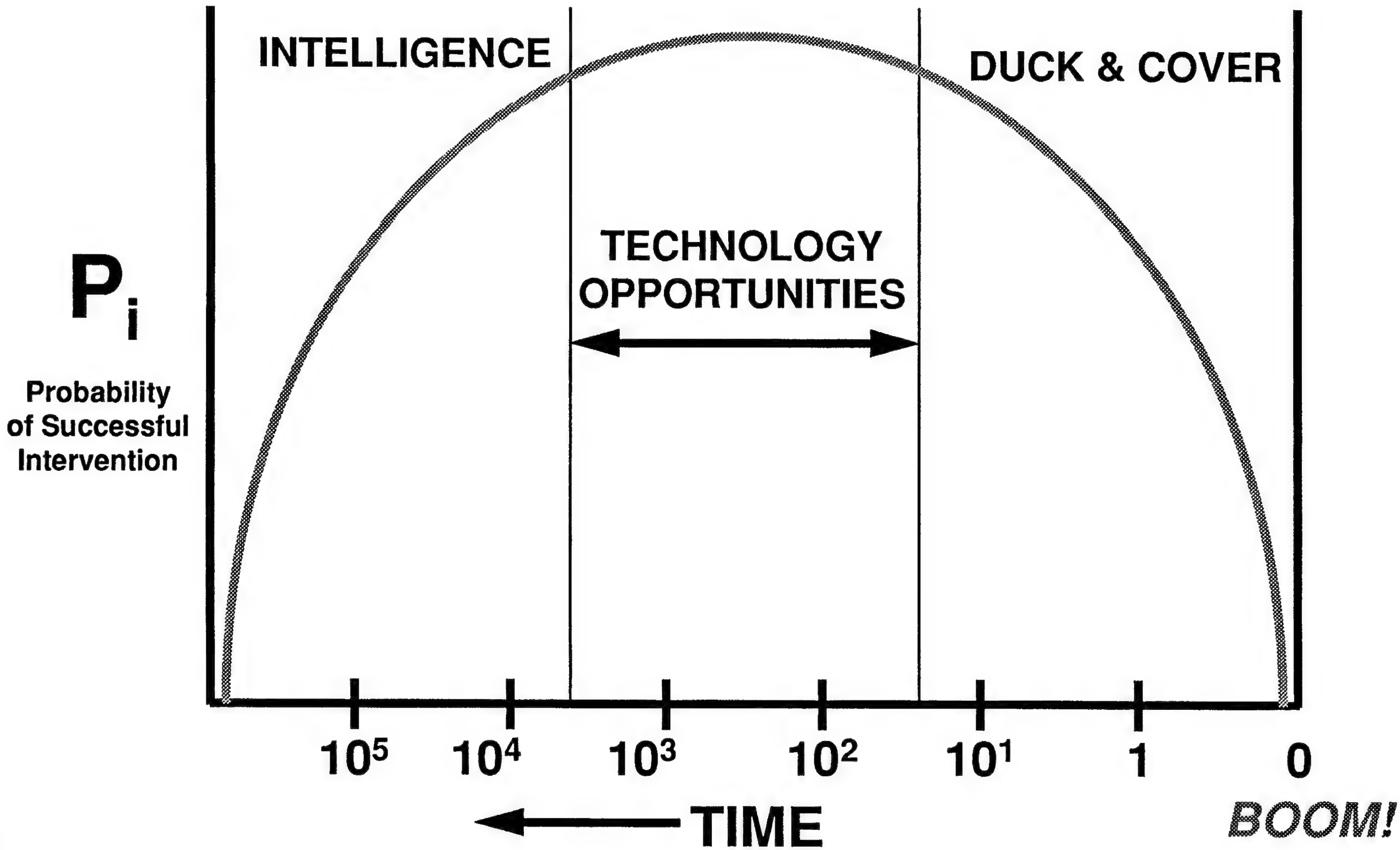
- In keeping with the limited time available for the brainstorming session, the threat scenario was narrowed to:

Military base: foreign and U.S. locations.

High-profile civilian targets.

Nitrogen-containing explosives.

THE LEE BUCHANAN CURVE



DETECTION AT PORTALS

- Sensors for particulates - explosive/high N cargo, vapors, fuel oil
- Technology: portal air shower, chemical detector (sampling) dogs, swipes (outside of vehicle), test driver's hand (see below), electronic sniffer for detonator EMI signatures.
- Wrong driver? - Hand sensor suite to measure "nervousness" via physiologic parameters (augment with voice tremors), verify ID with hand/ fingerprint, chemical sensors for explosives.
- Correct truck/cargo? - Sensors to ensure that everything is as expected: vehicle transponders, license plate scanning, cargo transponders.
- Cross-correlation of information is key!!!

DETECTION AT PERIMETER OR WITHIN ENCLAVE

- Advanced, hierarchichal surveillance & interrogation.
- Intelligent, wireless, low-cost, weatherproof, distributed sensors (thermal, magnetic, acoustic, seismic, micropulse radar, etc.) with hierarchical “wake-up” from simple to more complex sensors, finally alerting people.
- Foveation: focus expensive, single-point sensors on "hot spots" automatically based on distributed sensor signals.
- Physiologic model: look for changes and provide intelligence to avoid false positives.

DETECTION AT PERIMETER OR WITHIN ENCLAVE

- Mobile, autonomous detection platforms:

  - UAVs patrolling perimeter, wired into sensor network.

  - Augmented canines with GPS, transmitter, sensors including video camera, "trouble switch" to alert humans.

- Rapid-response, directed interrogation when suspicious objects/people detected: send guard dogs/people, turn on cameras/ audio.

DEFENSIVE MEASURES: FACILITY DESIGN/RETROFIT ANALYSIS

- Facility design/retrofit analysis.

- Software/expert systems to identify blast threat to facility or base.
  - Determine extent of vulnerability
  - Establish keep-out zones
  - Guidance for construction changes/retrofits
  - Identification of optimum portal areas

- Key is understanding blast behavior and performance of structures against them.

DEFENSIVE MEASURES: BUILDING/ FACILITY FORTIFICATION

- Expand earthquake technologies (active and passive) to mitigate blast effects
  - Carbon fiber column wrap, reinforcing "wall paper"
  - Smart, reactive materials and actuators
- Reactive blast protection
  - Deflective shields, deployable structures (fluid-filled bags, "foamcrete," etc.)
  - Opposing, cancelling blast (similar to reactive armor - either mechanical or explosive)

DEFENSIVE MEASURES: DISABLING BOMB/BOMBER

- Techniques for causing slow burn vs explosion:
  - Laser, microwave ignition
- Detonator disruption:
  - EMP pulses or other EM energy to interrogate and negate detonator mechanism
- Disable/disrupt bomber:
  - Non-lethal technologies before leave weapon delivery vehicle (foams, nets)
  - Tagging for future actions

SUMMARY

- Among the ideas generated, there are DARPA-appropriate projects that could have a major impact on anti-terrorism capabilities.
- Hierarchical, distributed sensing systems.
- Autonomous sensor systems.
- Multi-modal sensor suites to interrogate drivers/vehicles.
- Facility analysis/retrofit and advanced blast protection schemes.
- Techniques to detect/modulate/defeat explosive devices.

Counter Terrorism Workshop

July 11, 1996

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CONDITION-BASED MAINTENANCE
HELICOPTER ROTOR UPDATE

A. Evans, E. Cross, D. Ferry,
J. Hutchinson, R. Lytikainen, T. McGill, R. Rapp

EXECUTIVE SUMMARY

Objective

Robert Pohanka of the Office of Naval Research arranged a two-hour session for the afternoon of DARPA Day to inform the DSRC of recent research in monitoring fatigue damage and wear in rotors and gear boxes in the H-46 helicopter. In July 1992 the Council ran a rump workshop at the request of the Navy to review some of the catastrophic fracture problems in rotors and gear boxes plaguing the H-46 at the time. The 1992 DSRC report made recommendations specific to the fracture problems along with suggestions for longer term approaches to sensing and diagnosing fatigue damage in critical structural components. This year's session provided an update on the Navy's efforts to implement the elements of a Condition-based Maintenance regime for the H-46 and other helicopters.

DoD Relevance

The H-46 represents the prototypical case of life-extension of an aging system which remains in service with no replacement scheduled for the near future. The H-46 rotors now require approximately one hour of fatigue crack inspection for every hour of flight. Several components must be inspected at least once for every ten hours of flight. Performance restrictions are severe. An in-flight crack sensing system, combined with diagnostic and prognostic capabilities, is urgently required for effective life-extension.

Summary of Scientific & Technical Issues

The implementation of a condition-based maintenance system for the H-46 is one of the most pressing life-extension challenges for high performance structural components in military systems. There are a number of thrusts to the effort. The two emphasized at the workshop focused on the gear box and the rotor. Failure of either of these components is almost always catastrophic. Marty Chamberlain of ONR, who coordinated the presentations to DSRC in 1992, provided an overview of the steps the Navy has taken to deal with the H-46 aging components, and he outlined several of the programs directed towards Condition-Based Maintenance (CBM) of the H-46 started since 1992. The H-46 rotors continue to be of great concern, and there are indications that similar difficulties have cropped up with rotors on at least one other craft. Replacement of the rotors for the H-46 is scheduled with rotors made from a new material, a high strength stainless steel (PH13-8Mo). The replacement process is slow, however, and it will be some years before most of the H-46 will have new rotors. In the 1992 report, the Council recommended that a fracture mechanics analysis be performed on the critical components of the rotor with the purpose of identifying critical crack lengths and locations. This information should provide further rationale and guidance for the inspection regime. An analysis of this type is essential for

critical components susceptible to catastrophic cracking. So far this analysis has not been carried out. We remain convinced that it should be done. The fracture analysis will be applicable to the existing rotors as well as their replacements.

Robert Kolesar of NRaD described the development of an Air Vehicle Diagnostic System (AVDS) for providing real-time sensing and diagnosing of the H-46 gearbox. Multiple acceleration sensors collect surface motion data from different locations on the box. These accelerometers are expected to identify gear and bearing wear and faults such as chipped gear teeth, but not small fatigue cracks. The sensor data is processed to provide a number of "feature vectors" characterizing performance states of the gear box. The feature vectors are fed into a system of neural nets which has been trained to recognize abnormalities in the vectors. Abnormalities are flagged by the system and the pilot is alerted. Visualization of the feature vectors was demonstrated but will not necessarily be included in the operational system. Training is accomplished by the sequential substitution of critical components having representative faults in a gear box mounted on a test bed. Data on current flight operating conditions is taken into account in processing the feature vectors. To date, AVDS has been employed on a trial basis to locate faults in H-46 gearboxes, with one clear success and no false alarms.

Jeff Schoess with Fred Malver reviewed the status of Honeywell's effort to develop a Rotor Acoustic Monitoring System (RAMS). The system employs piezo-electric sensors to record acoustic emission data emanating from fatigue cracks opening and closing under cyclic loads. The sensors are mounted directly on the surface of critical components of the rotor. Packaged with each sensor is a telemetry module for wireless transmission of the sensor signal to a central processing unit. A major open question is whether the system can discriminate acoustic emission events from small cracks (<0.04 inches), especially when they are embedded within the heavy background noise inherent to the rotor environment. Experience in crack identification using RAMS has been gained with the help of a component with a pre-machined notch to initiate a fatigue crack. The component was quasi-statically cycled in a test rig without accompanying rotor noise. Since it is clearly not possible to introduce flaws in an operational rotor, Honeywell has developed a piezo actuator to "ping" components in a manner which attempts to simulate emission from a small crack. This artificial crack will be used to simulate acoustic emission events amid the noise in actual flight conditions, with signal analysis performed to discriminate the events. In the discussion of this approach, concern was raised because the frequency range excited by the pinger is much below that of crack emission.

Success in this effort will constitute an important advance in the development of systems for crack detection in characteristically noisy machine environments. Nevertheless, detection is only a part of a complete diagnostic/prognostic system. Once a crack has been detected, an assessment must be made of its criticality. Does the pilot have only seconds to respond? Or, can he proceed with his mission? Must the damaged component be replaced immediately, or is the crack sufficiently innocuous such that it can be dealt with at the next scheduled maintenance? These are obviously critical issues for the H-46, but they are also representative for many high performance structural components. Details of crack size and location are important in informing such decisions—simple knowledge of a crack's existence is not enough. (In this connection, it is not certain that acoustic emission is capable of discriminating fatigue cracks with different sizes.) Once a crack is located and its size is estimated, remaining safe flight life must be assessed using flight load histories. This also entails a fracture analysis of critical components to map the critical crack size with crack location.

Addressing the general issue of CBM, David Nagel of the Naval Research Laboratory pointed out a major need within the Navy's fleet of surface ships for sensor/diagnostic systems (MEMS

diagnostic systems on a chip, or DSOCs) for machinery, such as valves, tanks, drive trains, pumps, etc. Estimates for the number of accelerometer-based devices needed for naval applications range to the tens of millions. In addition to the evident importance of MEMS systems for fault detection in machinery, the discussion addressed the need for other types of sensor capable of detecting fatigue cracks. These include piezoelectric sensors for acoustic emission monitoring, as well as, perhaps, infrared detectors for sensing heat emitted by fatigue cracks.

The Navy's presentation emphasized the importance of combining sensor technology through modeling to life prediction. Pohanka stated the need for an integrated approach to the methodology, which is not yet being pursued. His reason for bringing the issue back to the Council stemmed from his view that the Council was one of the few groups in existence with the full breadth of expertise needed to address the problem: sensors, electronic processing and packaging, materials engineering, and fracture mechanics. In addition, DARPA is currently funding work on advanced signal processing directly related to wavelet-based helicopter flaw diagnosis and prognosis (under Anna Tsao).

Conclusions

The message brought to the Council is that a full methodology for flaw detection, diagnostics and prognostics for critical structural components remains to be implemented. A broad integration across the boundaries of electronics, materials and mechanics is required, and the Council is well positioned to scope the task. We propose that the Council hold an off-line workshop directed broadly at prognostic systems for condition-based maintenance, with special attention to systems for the H-46, and perhaps other aging systems that must remain in the DoD operational inventory.

CONDITION-BASED MAINTENANCE

(Helicopter Rotor Update)

A. G. Evans, L. E. Cross, D. Ferry,
J. W. Hutchinson, R. Lytikainen, T. McGill,
R. A. Rapp

Objective

Review of Navy's efforts to implement systems for monitoring fatigue cracking and wear in H-46 gearboxes and rotors, updating DSRC recommendations on rotor problems in 1992.

DoD Relevance

1. Life extension of H-16 helicopter

2. Prototypical systems for condition-based maintenance

Technical Summary

1) Gearbox

Aviation Vehicle Diagnostic System (AVDS) has been implemented for monitoring wear

- Performance state "feature vectors
- Neural Nets
- Successful preliminary trial employment

2) Rotor

- Replacement rotors scheduled with material having improved properties

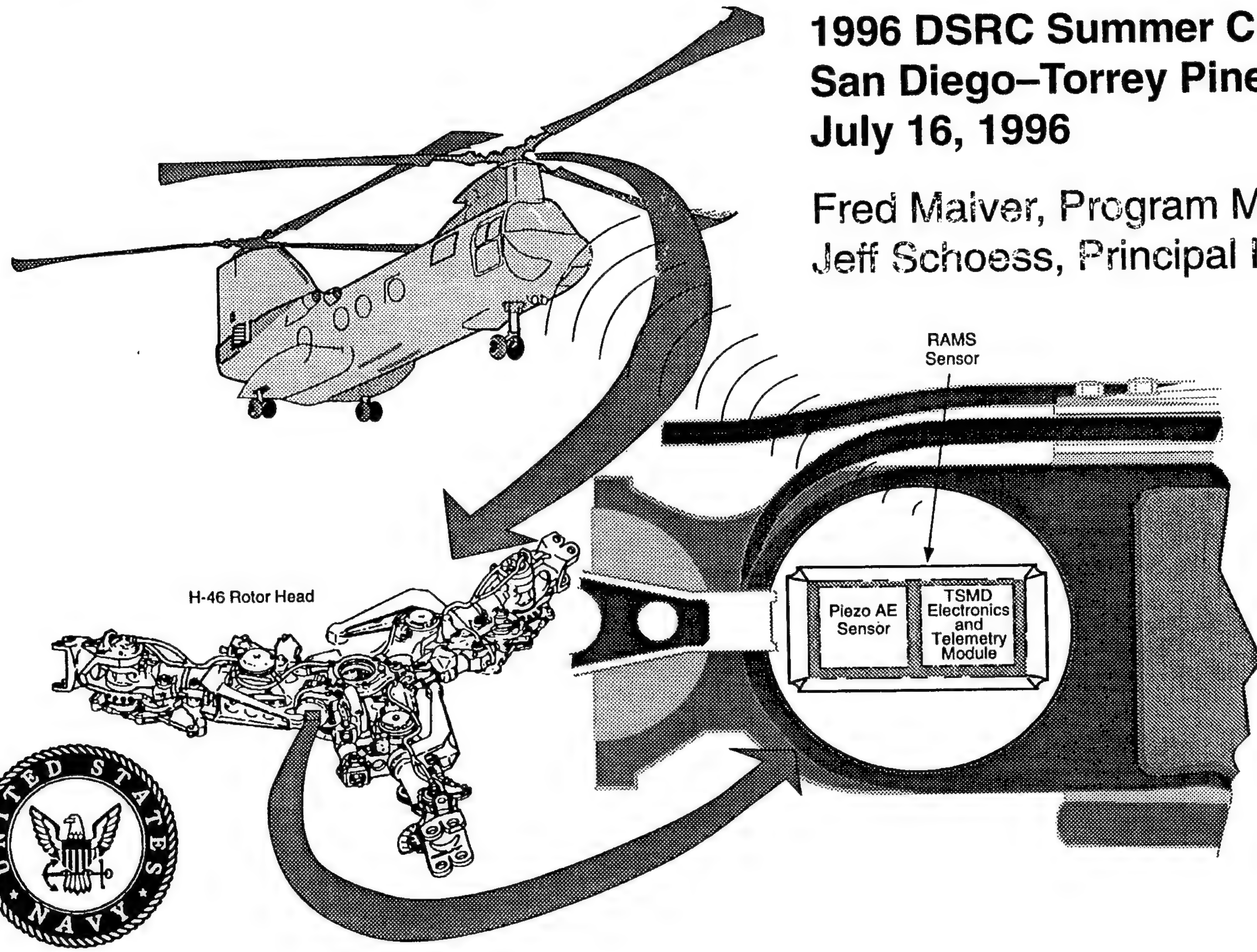
- Acoustic monitoring system under development

  - Acoustic emissions (AE) from fatigue cracks sensed using transducers located on rotor components
  - Training on cracked components in test rig
  - Simulation of cracks by "pinging" components under flight conditions

Rotor Acoustic Monitoring System (RAMS)—Technology Review

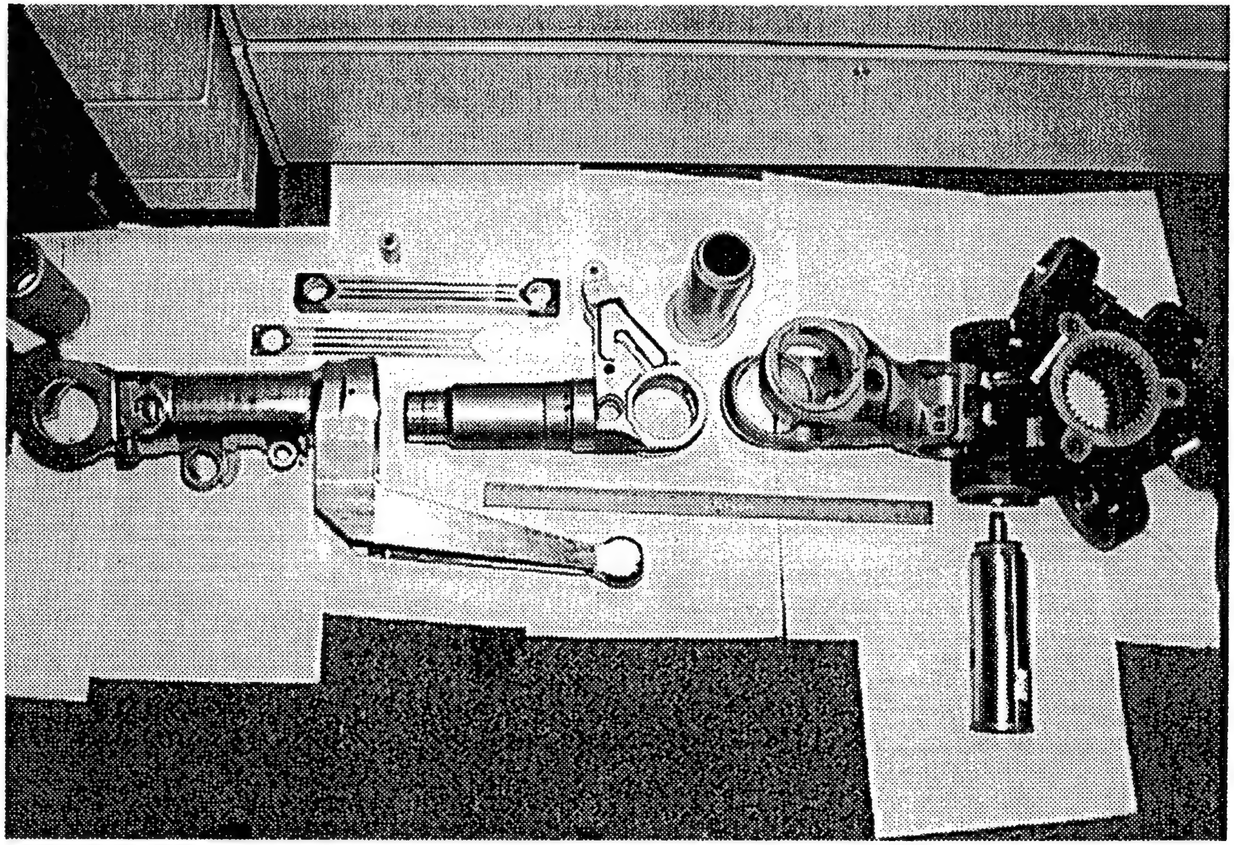
1996 DSRC Summer Conference
San Diego–Torrey Pines
July 16, 1996

Fred Malver, Program Manager
Jeff Schoess, Principal Investigator



Honeywell

H-46 Rotor Head Layout



Honeywell

Rotor Monitoring System

Status & Challenges

- Progress implementing acoustic emission (AE) monitoring system
- Discrimination between AE events and back-ground noise remains to be demonstrated
- An integrated system (sensors, diagnostics and prognostics) remains to be formulated

DARPA/DSRC Opportunity

Scope prognostics methodology for critical structural components using council expertise in sensors, MEMS, packaging, materials and mechanics.

Condition-Based Maintenance (Helicopter Rotor Update)

J. Hutchinson, E. Cross, A.Evans, C. Evans, D. Ferry, B. Gilbert, G. Kovacs, A. Heuer, R. Rapp and R. Lytikainen

July 16, 1996

3:15 p.m.	**Overview/Introduction** R. Pohanka (ONR)/M. Chamberlain (ONR/Jason Assoc.)
3:30 p.m.	**Neural Network Gearbox Diagnostics** R. Kolesar (NRAD/NCCOSC)
4:00 p.m.	**Helicopter Rotor Head Diagnostics** F. Melver (Honeywell)
4:30 p.m.	**Condition-Based Maintenance—ONR Vision** D. Nagel (NRL)
5:00 p.m.	**Discussion**
5:30 p.m.	**Adjourn**

Condition-Based Maintenance (Helicopter Rotor Update)

July 16, 1996

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DARPA/DSRC MILITARY VISITS
(EXERCISES, WARGAMES AND CONCEPT DEMONSTRATION)

R. Lytikainen

EXECUTIVE SUMMARY

Objective

The DSRC directly supports DARPA's primary mission of sponsoring research and development (R&D) activities to seek, apply and/or insert the newest advances in science and technology for the military user. As the modern military encounters a nontraditional, regional, littoral set of threats and is given nontraditional missions such as peacekeeping, pacification and counter-terrorism, operations-other-than-war (OOTW), Detection of Unexploded Ordnance (UXO), Biological Weapons Defense (BWD), small unit operations and combat casualty of the individual soldier, have stepped to the fore. We need to understand where technology can help, and where it cannot. Our series of DARPA/DSRC Military Visit and Exercise activities make us smarter and more innovative in finding ways to use our academic, commercial, and economic strengths to become better tools of national defense policy. The exposure of leading edge technologists, scientists and engineers to the way the military does business via participation in and observation of operational exercises, military unit visits and wargames, continues as an excellent venue for DARPA program managers and DSRC scientists.

Relevance to DoD

All military exercise and unit visits are DoD relevant by definition. DARPA works directly with military units on field concept demonstration projects, with approximately two thirds of our visits combined with such directed activities.

Prototype development and concept demonstrations conducted or planned during the past year include; flexible photovoltaics, HTSC/cryo-coolers, high performance power sources (rechargeable battery and fuel cell technology), low-power/compact electronics, helmet-mounted displays (Tactical Information Assist (TIA), Pathfinder, VUMAN, FROGMAN), LWIM, microinstrumentation cluster, MEMS, environmental technologies (supercritical water oxidation/SCWO)/HAZMAT disposal (at-sea), UXO/land mine detection, biological weapons defense (BWD), and initiatives for remote combat casualty care and personnel status monitoring.

Activities

Off-Conference

Since the 1995 DSRC Summer Conference, DSRC scientists and DARPA program managers participated in 23 separate military exercises, military installation visits and wargames. The "off conference" visits are usually set up in conjunction with the Navy/Marine Corps "Naval Science Assistance Program (NSAP)", the Navy's "Scientist-to-Sea", the Army's Field Assistance in Science and Technology (FAST) and Scientists and Engineers Field Experience With Soldiers (SEFEWS) programs. Air Force visits are set up directly with operational commands, since they have no "field"

science advisor program. DARPA/DSRC is also linked with the Air Force "TECH CONNECT" program, which acts as a conduit for finding answers to questions ranging from "low-tech" to "hi-tech" issues that can assist the military today.

On-Conference

"On-conference" visits during the 1996 Summer Conference reflect the shifting priorities within DoD and DARPA and were organized around themes of mine detection and explosive ordnance disposal, BWD and combat casualty care. It is interesting to note that despite remarkable advances in technology, the best detection capability for UXO/land mines is "dog sniffing", and the best detection, classification location and marking capability for sea mines (including moored, proud and buried), especially in very shallow water (VSW) and shallow water (SW) zones, is the Atlantic Bottlenose Dolphin operated by the Navy Fleet Mammal Program.

Visits during the past year included 25 DSRC, 40 DARPA, 32 Navy and Marine Corps, Office of Naval Research (ONR), NSAP Science Advisors and 106 DARPA contractors, for a total of 203 military activity-person visits. Some DSRC and DARPA personnel participated in more than one of the following activities:

- **Exercises/Concept Demos**

– Marine Corps Air Ground Combat Center 29 Palms, CA	"Steel Knight" "Desert Fire Exercise" (2 visits) Air/Ground Combat Training – Flexible PV, LWIM, TIA,

PATHFINDER, VUMAN, Micro Instrument Cluster, Concept Demos

– U.S. Army III Corps, 4th Infantry Division Fort Hood, TX	Force 21, armor (M1A2 tank, artillery exercise), simulation & modeling (SIMNET)
– Explosive Ordnance Disposal Technology Division (EODTECHDIV) Joint/Navy/ Marine Corps/Army/Air Force Indian Head, MD	Mine sensing, defusing, disposal demonstration (land and sea mines)
– Navy Aegis Destroyer at-sea SOCAL OPAREA	USS John Paul Jones (DDG53) Independent Steaming(ISE), Helicopter calibration tests

- **Military Installation Visits**

– Marine Corps Base (3 visits) Quantico, VA	MEMS PI Visit, Commandant's War Fighting Lab (CWL), LWIM Demo
– Navy Fleet Mammal Training (2 visits) NRAD, Point Loma,CA	Training/Demonstration MK4, MK7 System Demo

– Naval Air Station (2 visits) Patuxent River, MD	F-14, E-2C, F/A-18, P3-C Avionics/electronics cryo coolers, conformal IR A/D-D/A packaging
– Naval Air Station Whidbey Island, WA	EA-6B Avionics/electronics/EW A/D-D/A packaging
– Navy Amphibious Ship in-port 32nd St Naval Station, CA	USS Boxer (LHD4)
– Explosive Ordinance Disposal Unit (2 visits) Coronado Island, CA	EODMOBUNIT3 [1] Minehunting, Exploitation, MK-7 Mammal, MK-16 Diving Rig
– Naval Air Station (2 visits) Helicopter Combat Squadron (HC-3) North Island, CA	CH-46 Helicopter Rotor, Gearbox Diagnostics/Prognostics
– Naval Air Station Helicopter Surveillance Squadron (HSL-41) North Island, CA	CH-53 (Lamps) Helicopter Rotor, Gearbox Diagnostics/Prognostics
– COMNAVSURFLANT Norfolk, VA MEMS	Diagnostics/Prognostics, CBM, In-situ sense/monitor-

• **Wargames**

– Chief of Naval Operations/ Naval War College National Ocean Intelligence Center (NOIC) Suitland, MD	"TIG-95" Wargame Technology Initiative Game

• **Military/DSRC Workshops/Meetings**

– "Condition-Based Maintenance-Helicopter Update" 1996 DSRC Summer Conference LaJolla, CA	ONR, COMNAVAIRPAC HC-3, DARPA, DSRC, NRL
– Navy "Smart Ship" DARPA Arlington, VA	DARPA, DSRC, ONR, Navy, "Smart Ship" Team Corrosion, coatings, in situ sensing

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[1] We experienced a timely (but unfortunate coincidence) in one of our visits to the Fleet EOD unit at Coronado Island. That morning visit came the day after flight TWA#800 was downed by an apparent bomb. Navy divers and EOD specialists were called in from several areas of the country to help look for the wreckage.

During the year, follow-up discussions took place among DARP and ONR program managers and DSRC scientists with the Navy's "Smart Ship" task force regarding candidate concepts for new corrosion-resistant coatings, new types of insulation and waste disposal techniques aboard ship with the purpose of reducing manning on current and next generation ships.

In addition to the above, a 1996 DSRC Summer Conference "Rump Session" on "Condition-Based Maintenance – Helicopter Rotor Update" (reported on pp. 265 to 276), was jointly organized by the DSRC and the Office of Naval Research (ONR) to provide feedback to the DSRC on a series of recommendations made to the Navy (many of which were instrumental in starting the Navy's CBM program) during the 1992 DSRC Summer Conference. A report on the "Detection of Unexploded Ordnance (UXO)" workshop also appears elsewhere in this document on pp.1 to 15.

Conclusions & Observations [2]

While the DARPA/DSRC Military Visit program has matured considerably in recent years, successful technology insertion is directly correlated with the continuing education of new program managers and new council members as they come aboard, and as the needs of DoD continue to evolve. While most DARPA Program managers and many DSRC members have participated in military visit activities and are developing better understanding of what the warfighter needs, DARPA/DSRC focus must remain on defense application of emerging technologies, look for ideas to help solve current, practical, day-day problems of the warfighter ... And constantly look ahead for opportunities for technology to help, where it can help. The challenge that is now before us, is to try our best to do something with the knowledge we are acquiring, and keep in mind the charge given by Admiral Issac Kidd to his Navy when he was the Chief of Naval Material in the early 1970s:

"WHYDFTFT?"[3]

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(2) A summary of the DARPA/DSRC Military Visit/Exercise/Wargame and Concept Demonstration presentation given on "Wrap Up Day" is provided on the following pages.

(3) "What Have You Done For The Fleet Today"?-ADM Ike Kidd, circa 1973

30 Jul 96

DARPA/DSRC Military Visits

(Purpose)

- Early Concept Demonstration of Potential Military Application and Technology Insertion
- Build Intuition via Exercises, Wargames, and First-hand Observation

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Links via Military Science Advisors

- Navy/Marines (NSAP, Scientist-to-Sea)
- Army (FAST/SEFEW)
- Air Force (TECH CONNECT, Direct)

30 Jul 96

DARPA/DSRC Military Visits

(Participants)

- DSRC - 30 or so "world-class" scientists, mostly academia, 29th year supporting DARPA/ARPA
- DARPA - 40 or so DSO/ETO program managers
- Other - 25 Navy/Air Force/Army Agents + Contractors

- Numbers - 510 person-visits, 65 Commands/Ships/ Operational Units - March 1992 to today
- Since 1995 Summer Conf:
  - 40 DARPA
  - 25 DSRC (+ One Invention)
  - 32 Navy,Marine Corps Agents/Science Advisors
  - 106 Contractors (22 + 84 MEMS PI)

  203

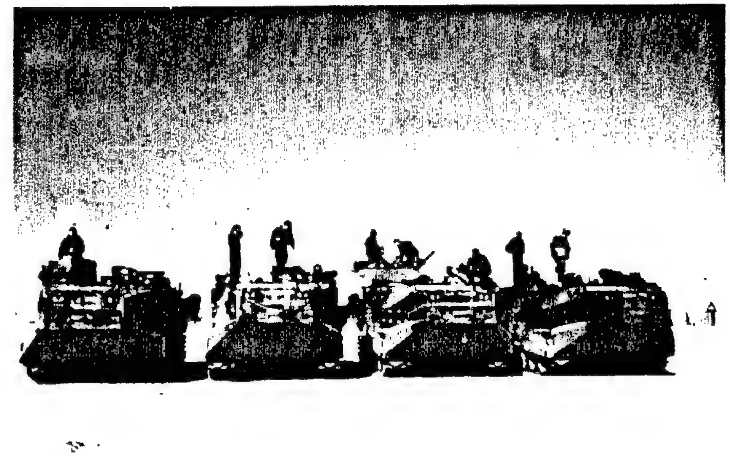
Current/Planned Concept Demos

- UXO/Land Mines, Anti-Terrorism -Marines, Army, Navy DSO
  (chemical detection, dogs +) (Dugan)
- Biological Weapons Defense (BWD), Combat Casualty Care DSO
  - Marines, Navy, Army (Donlon, Jones, Satava, Silva)
- LWIM, Microinstrumentation Cluster-Environ. Monitor, etc. ETO
  (MEMS, actuator/sensor) - Marines/CWL, Army, Navy (Gabriel, Ritts)
- HTSC (Cryo-coolers) -Marines, Army, AF, Navy DSO
  (antennas, radios, receivers, couplers) (Patten, Wolf)
- Tactical Info Asst (TIA), Pathfinder, VUMAN, FROGMAN ETO
  (small area, low-power displays) -Army, Marines, Navy, (Urban)
  CWL, Spec Ops (Bosnia)
- High Performance Power Sources -Marines, Army, Navy DSO
  (compact batteries, fuel cells, photovoltaics) (Dubois, Wax, Nowak)
- Electronic Packaging/Distributed Sensor Systems ETO
  (low cost instrumentation) -Marines, Army, AF, Navy (Lemnios)

MCAGCC, 29 PALMS, CA (DESFIREX – NOV 96)

(Kovacs, Lemnios, Naclerio, Paulette, Lytikainen) (1 Mar Div)

Getting Ready For Action



CAX Command Element

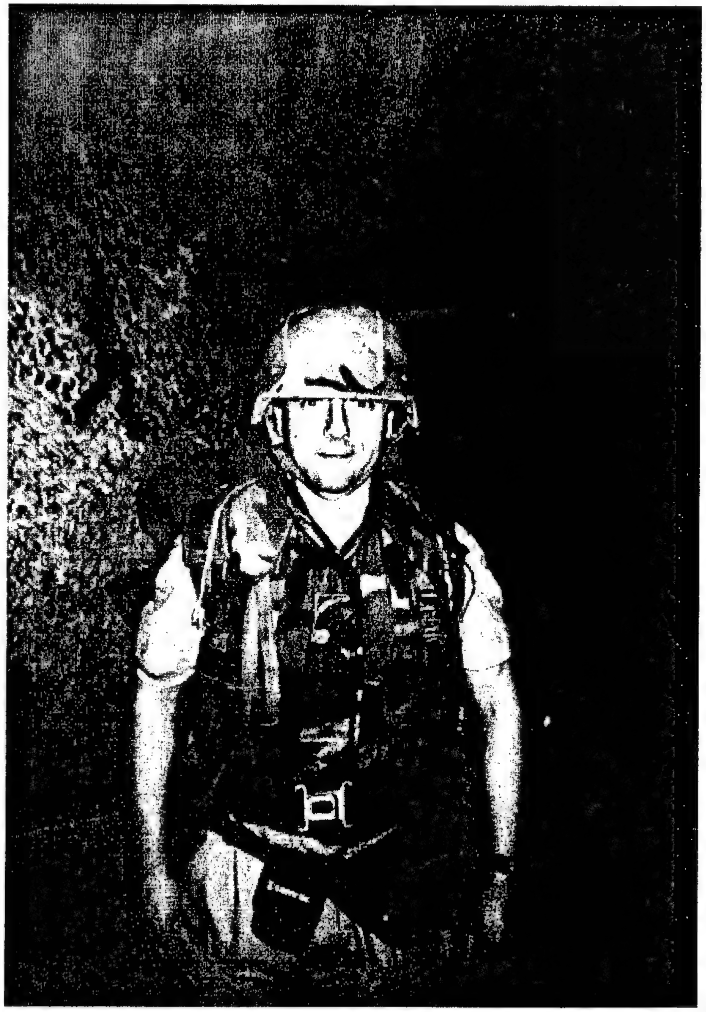
Boarding The LAVs

Hells' Angels (Since WWI)

808-6-4-96-28

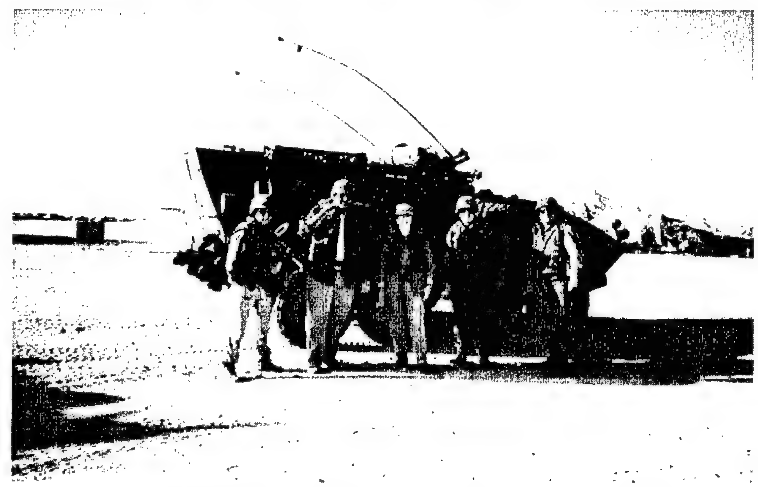
MCAGCC, 29 PALMS, CA (DESFIREX – NOV 95)

(Kovacs, Lemnios, Naclerio, Paulette, Lytikainen) (1 Mar Div)



Kovacs In Flak Jacket

Naclerio, Leidigh, Lemnios



Scientists, Flak Jackets and LAV

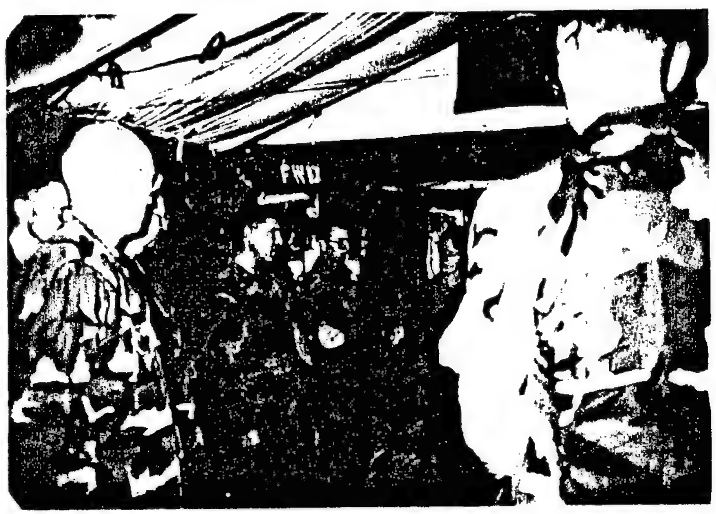
808-6-4-96-23

MCAGCC, 29 PALMS, CA (DESFIREX – NOV 96)

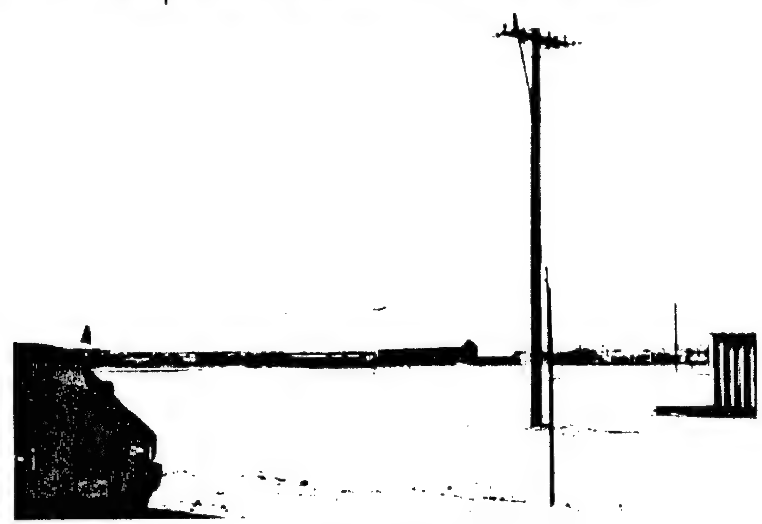
(Kovacs, Lemnios, Naclerio, Paulette, Lytikainen) (1 Mar Div)

Dr. Anita Jones, DDR&E, Arriving

Camp Wilson Rear Command Post



LGen VanRiper, MGen Libutti, Dr. Jones

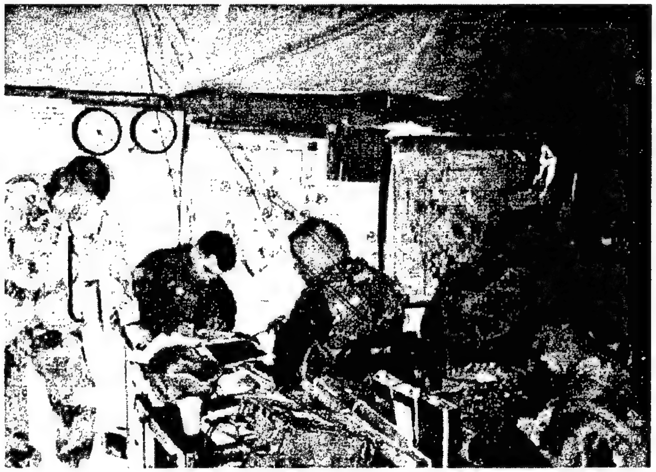


Dr. Jones Departing

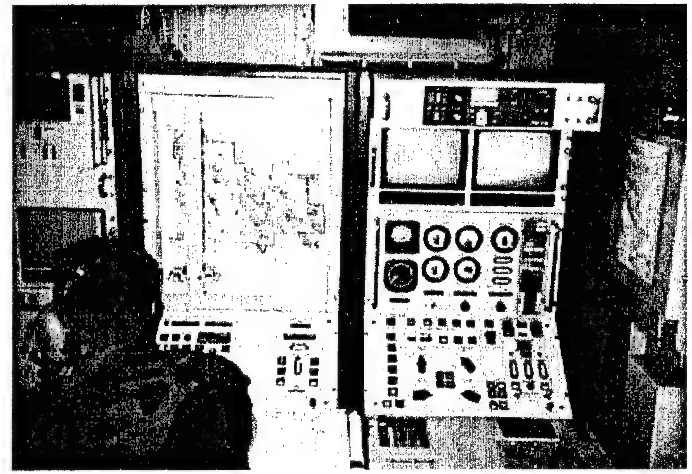
808-6-4-96 29

MCAGCC, 29 PALMS, CA (DESFIREX – NOV 95)

(Kovacs, Lemnios, Naclerio, Paulette, Lytikainen) (1 Mar Div)



7th Marine Mobile Command Post



PLRS Van

More mobile Command Post – LAV

Even More Mobile Command Post

808-6-4-96-27

MCAGCC, 29 PALMS, CA (DESFIREX – NOV 95)

(Kovacs, Lemnios, Naclerio, Paulette, Lytikainen) (1 Mar Div)

Instant MASH

Dr. Kovacs And RADM Wright, USN, MD

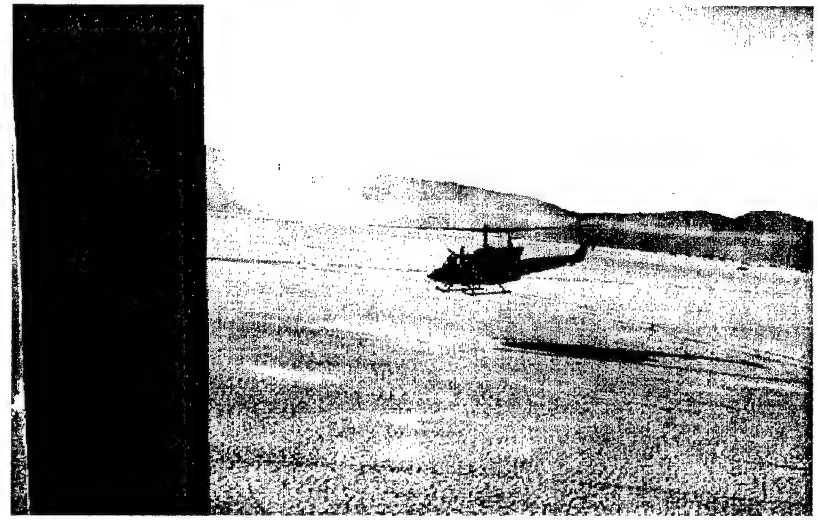
LT Ulnick, USNR, MD

808-6-4-96-25

MCAGCC, 29 PALMS, CA (DESFIREX – NOV 95)

(Kovacs, Lemnios, Naclerio, Paulette, Lytikainen) (1 Mar Div)

Choppers Ready To Party



UH-1 (Heuy)

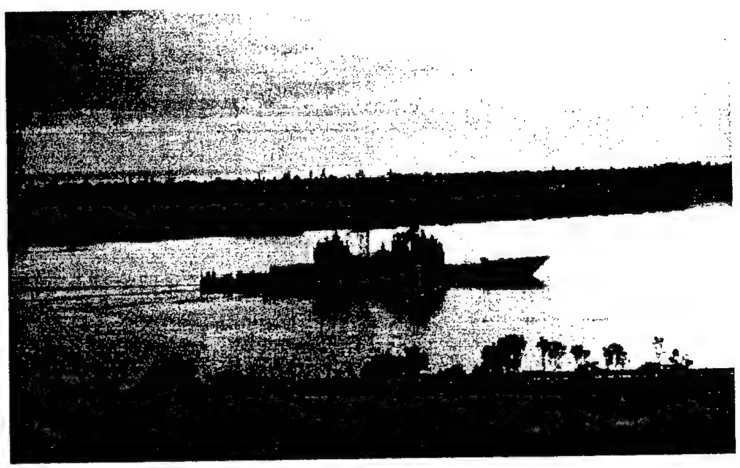
Helicopterman Apprentice Kovacs

808-6-4-96-26

USS JOHN PAUL JONES (DDG 53) (DEC 1995)

(At Sea, SOCAL OPAREA) (Bob Rapp)

Sea Bags Packed, Ready to Go



Sailing Into The Sunset

First Class Berthing

808-6-4-96-17

USS JOHN PAUL JONES (DDG 53) (DEC 1995)

(At Sea, SOCAL OPAREA) (Bob Rapp)

CH-46

LAMPS Helicopter And Rapp On The Fantail

Helicopter Approach Calibration Tests

808-6-4-96-18

EODTECHDIV, INDIAN HEAD, MD (FEB 96)

(Patten, Rolison, Toth, Wolf, Lytikainen)

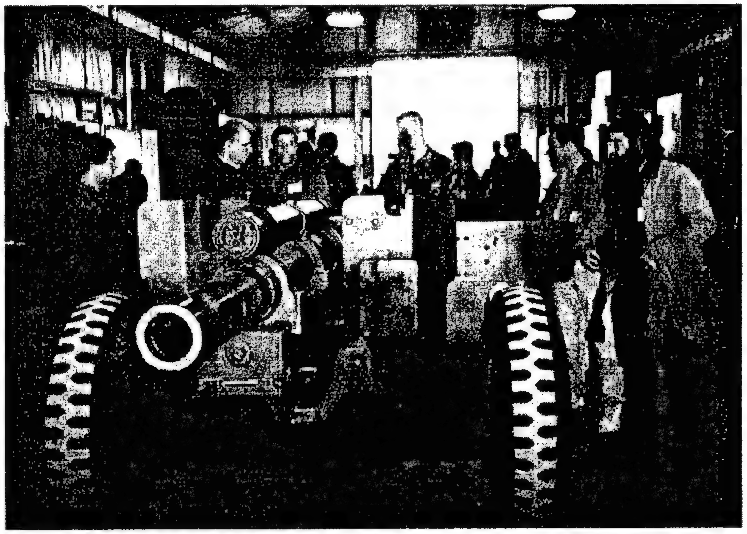
We Survived a Minefield—And Live To Tell About It!

(Army, Navy, Marine Corps, Air Force, DARPA/DSRC, NRL Mine Warfare Experts)

808-6-4-96-7

MARINE CORPS BASE, QUANTICO, VA (MAR 96)

(Ken Gabriel And 92 Of His Closest (MEMS PI) Friends Visit Marines)



The Business End of a Howitzer

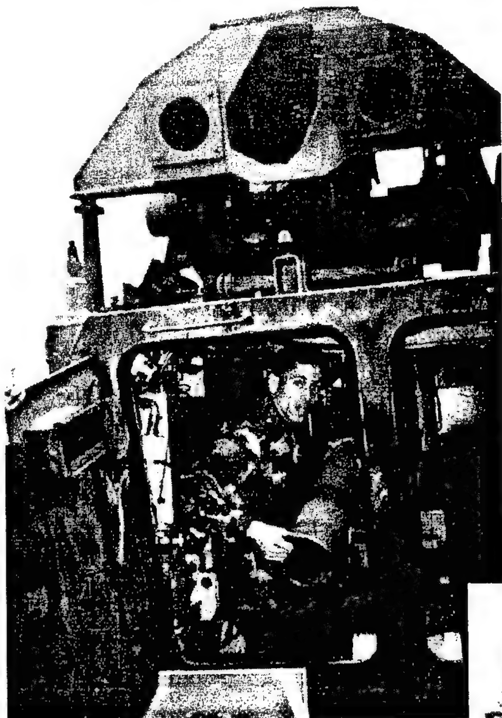
100 lbs and Counting!

So You Think You Wanna Be A Marine?

808-6-4-96-13

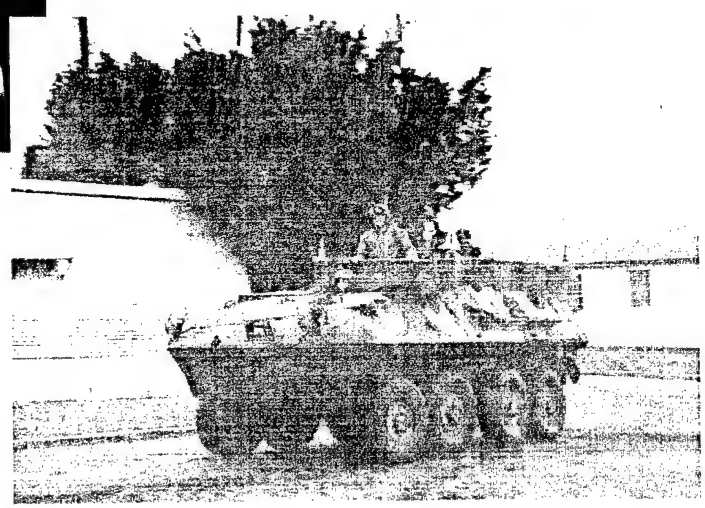
MARINE CORPS BASE, QUANTICO, VA (MAR 96)

(Ken Gabriel And 92 Of His Closest (MEMS PI) Friends Visit Marines)



Load And Lock!

Ready For Battle

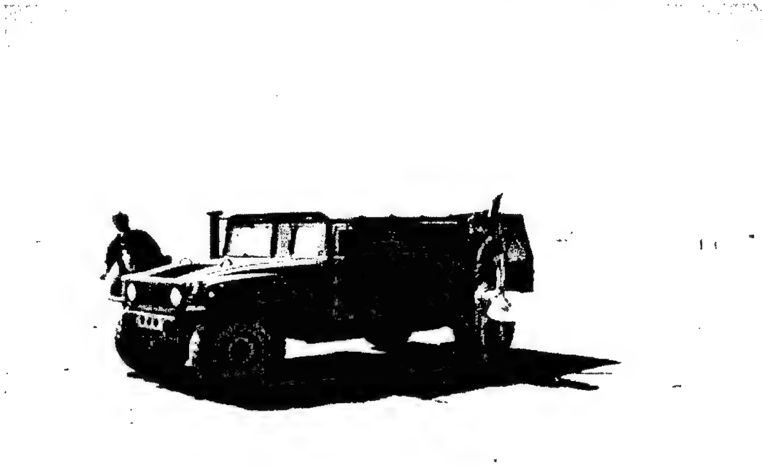


LAV–Fully Personed

808-6-4-96-14

MCAGCC, 29 PALMS, CA (DESFIREX – MAR 96)

(Wax, Malafsky, Kiers, Lytikainen)



Facing The Barren Wastes

Howitzer Lineup

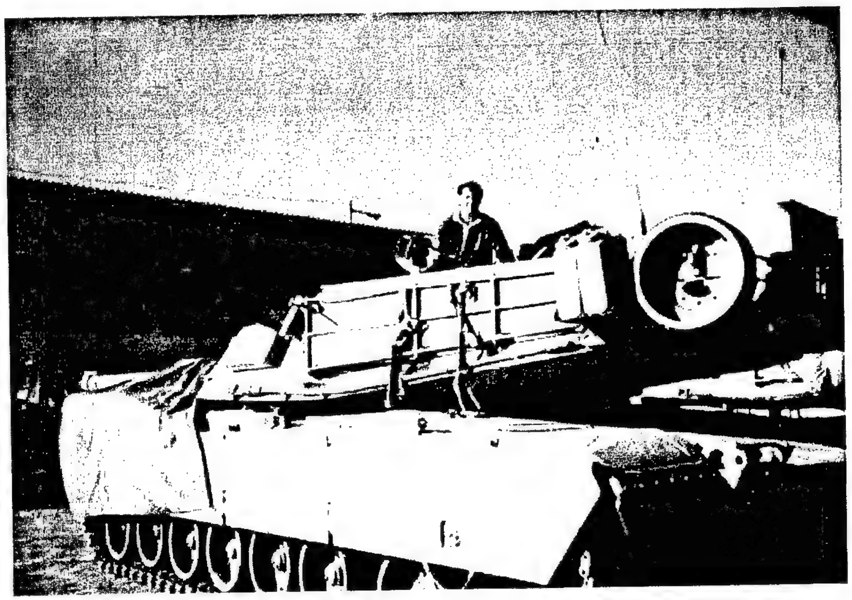
Marine And <u>His</u> LAV

Dr. Wax And <u>His</u> Limo

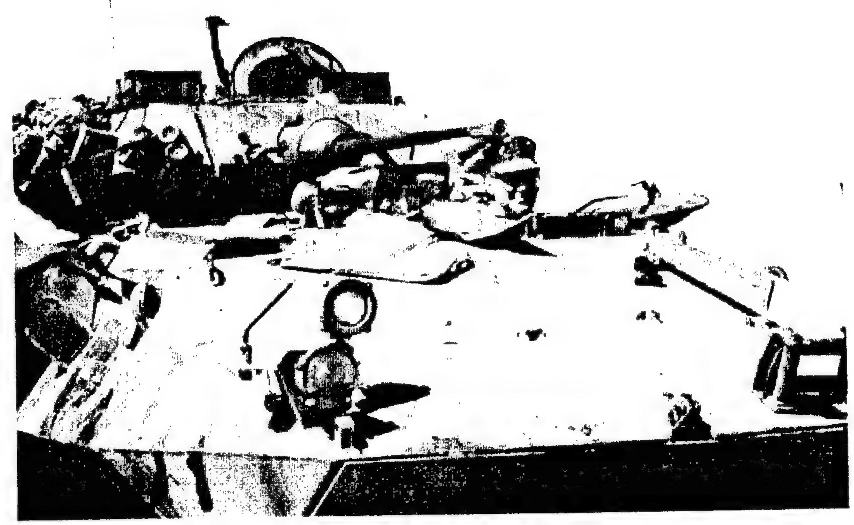
808-6-4-96-21

MCAGCC, 29 PALMS, CA (DESFIREX – MAR 96)

(Wax, Malafsky, Kiers, Lytikainen)



Steve (Dukakis) Wax And M1A1



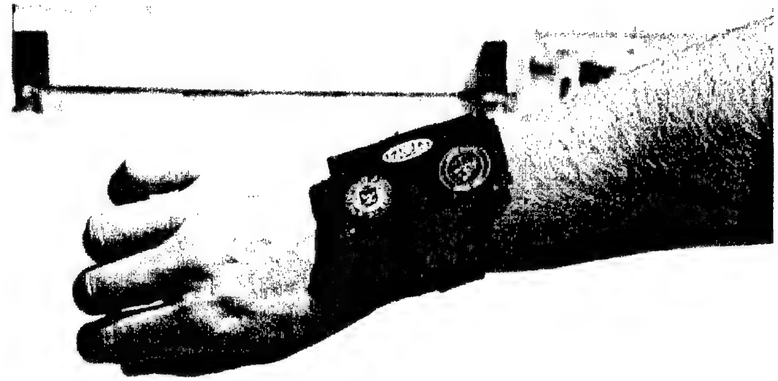
Driving a Land Attack Vehicle (LAV)

808-6-4-96-20

MCAGCC, 29 PALMS, CA (DESFIREX – MAR 96)

(Wax, Malafsky, Kiers, Lytikainen)

Photovoltaics(PV) Concept Demonstration



Automated Weather Station (AWS) Concept Demo

Dice-Playing Concept Demo

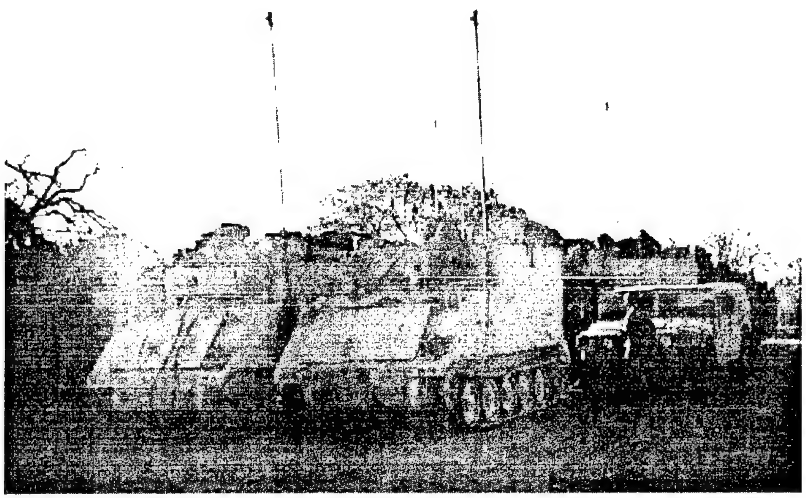
808-6-4-96-19

U.S ARMY III CORPS, FT. HOOD, TX (MAR 96)

(Osgood, Hui, Lytikainen) (1st Armored Division)

The Cavalry Is Coming

Command And Control – The Heat Of Battle



3ID Command Post Configuration

High Definition Tactical Displays?

808-6-4-96-9

U.S. ARMY III CORPS, FT. HOOD, TX (MAR 96)

(Minelaying, Detection And Clearing Operations)

Prime Suspects

Caught In The Act By The Recon Team

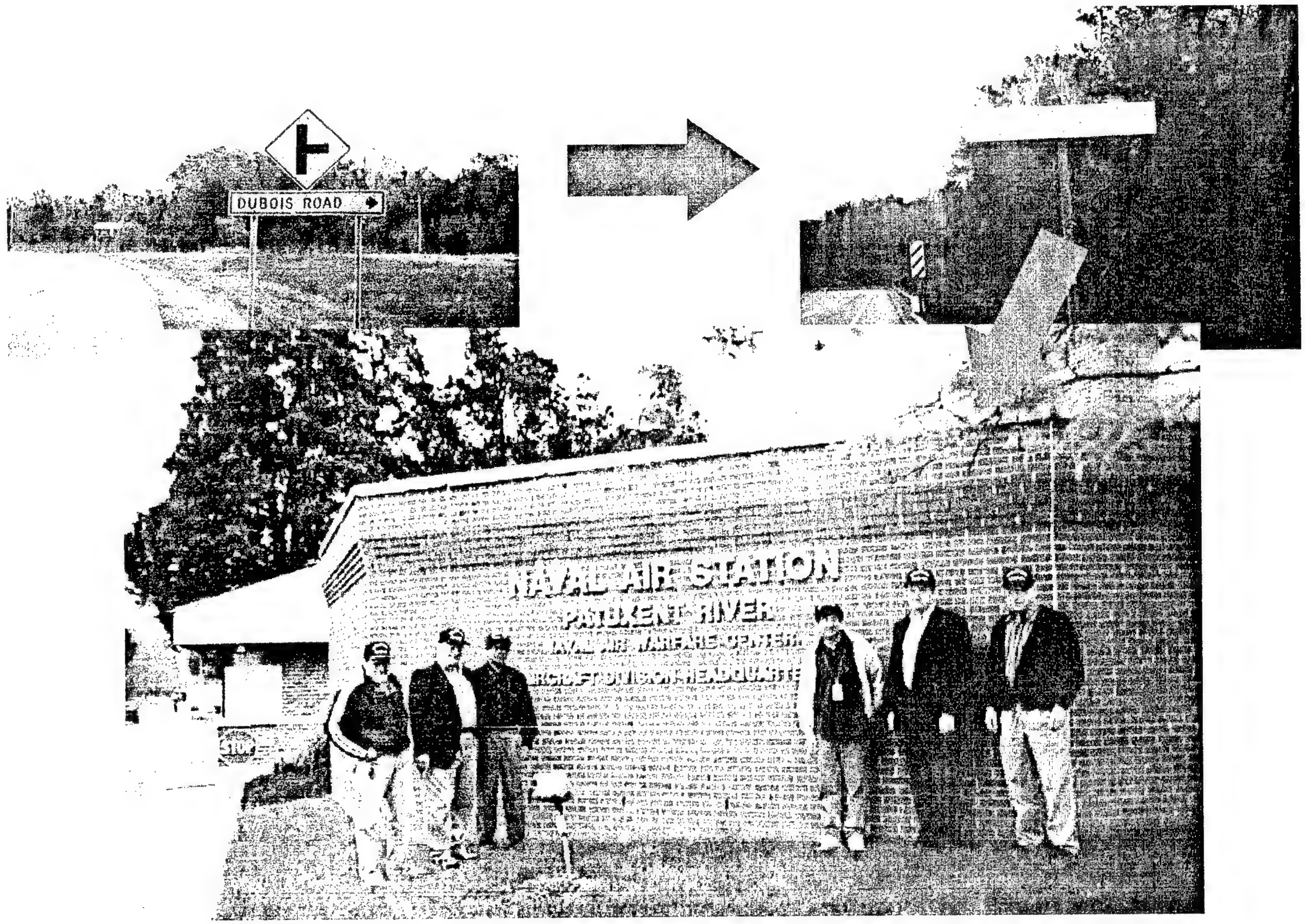
Is This Biological Warfare, Landmine Warfare, or Both?

This Calls For The M1A2 Mine Clearer!

808-6-4-96-8

NAS PATUXENT RIVER, MD (MAY 96)

(Balcerak, Durvasula, Husain, Patten, Wolf, Lytikainen) (F-A/18, F-14, P-3C)

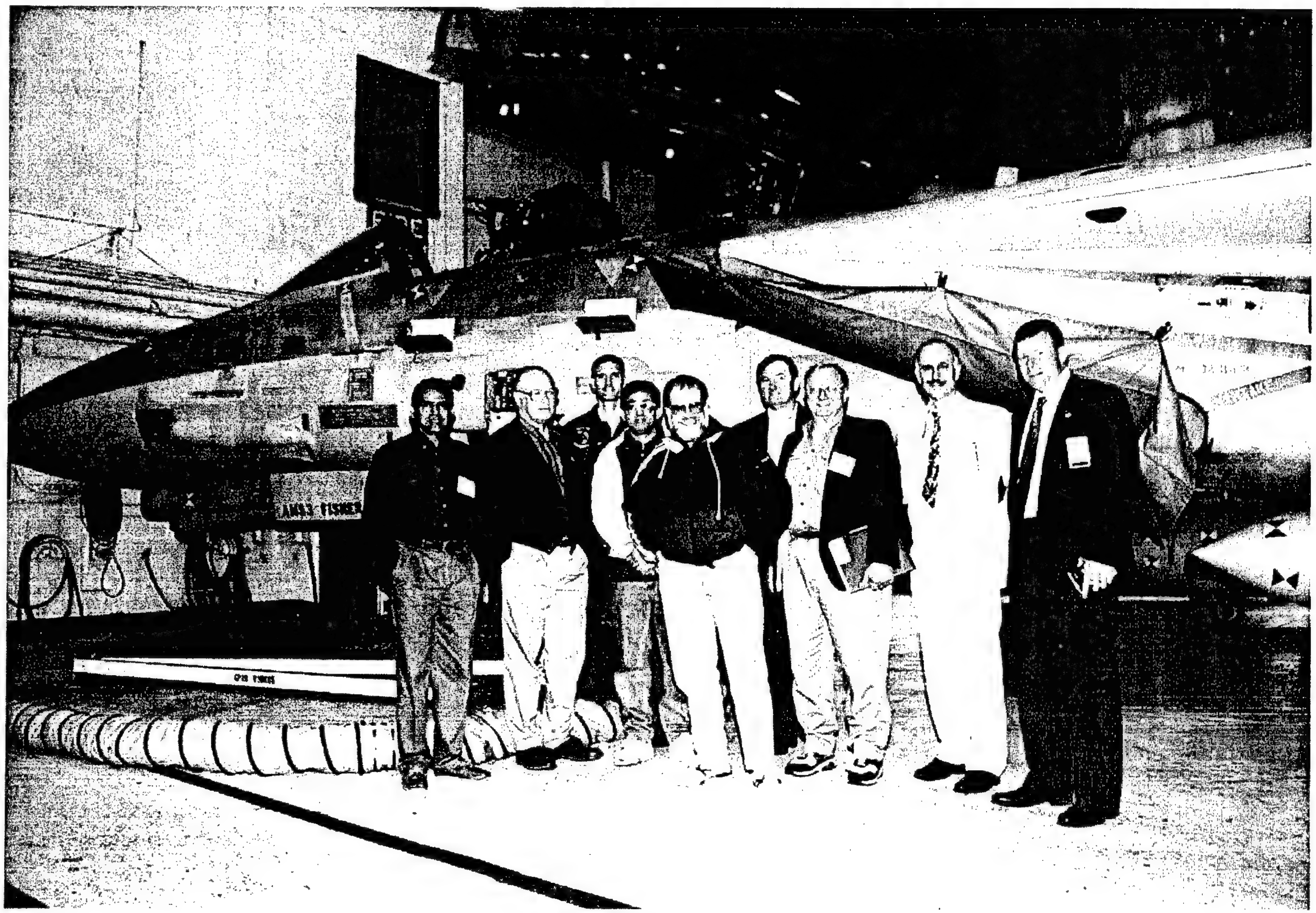


It's Not Easy To Get To PAX River!

808-6-4-96-1

NAS PATUXENT RIVER, MD (MAY 96)

(Balcerak, Durvasula, Husain, Patten, Wolf, Lytikainen) (F-A/18, F-14, P-3C)

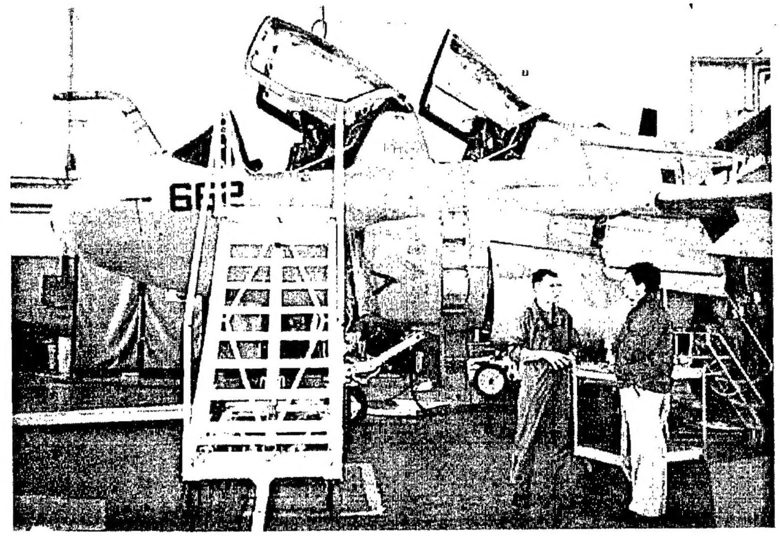


DARPA Group With F-14

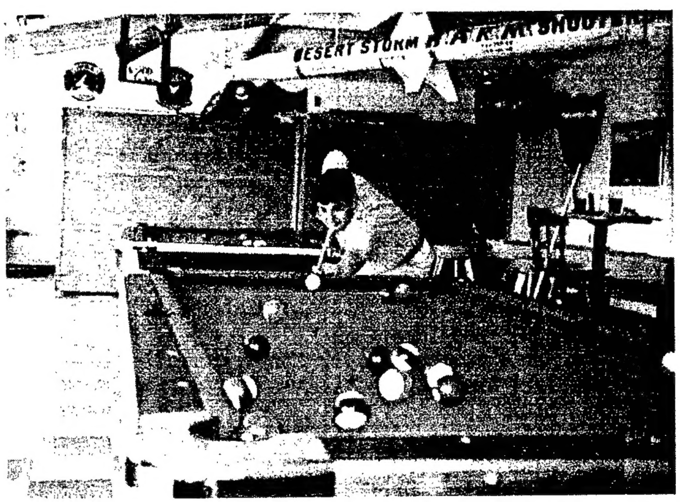
808-6-4-96-15

NAS WHIDBEY ISLAND, WA (MAY 96)
(Lemnios, Lytikainen) (EA-6B/Prowler)

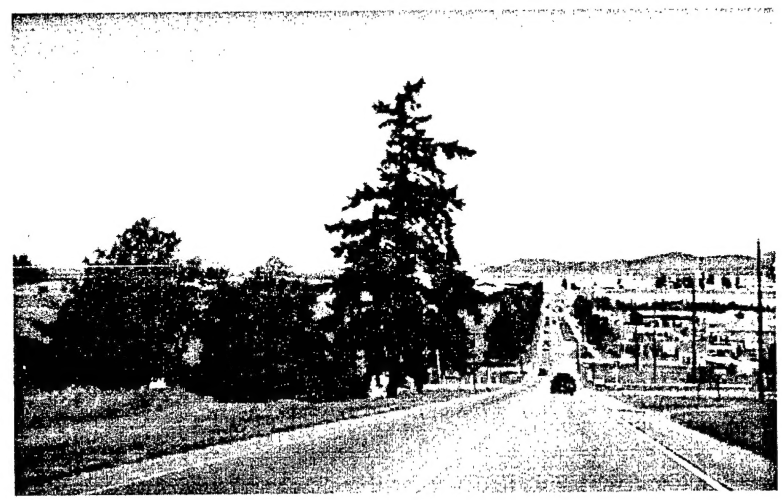
Mukilteo Ferry



LT Baker and Lemnios



Minnesota Fats?

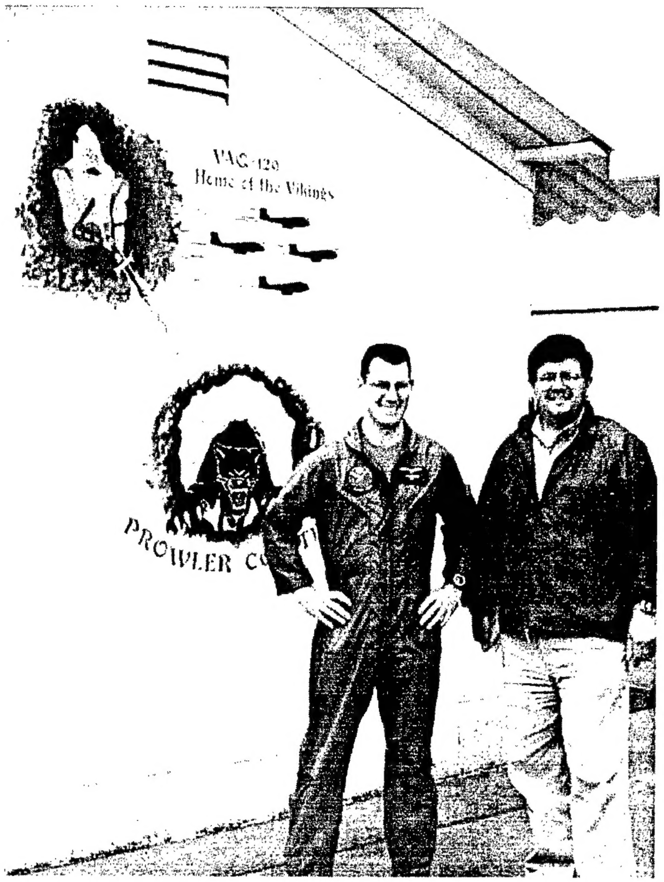


Viking Country

808-6-4-96-3

NAS WHIDBEY ISLAND, WA (MAY 96)

(Lemnios, Lytikainen) (EA-6B/Prowler)



Prowler Country

Front-Seater

EA-6B Receiver Group

808-6-4-96-4

July 1996

30 July 1996

DSRC SUMMER CONFERENCE MILITARY VISIT SCHEDULE

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
7	8 **DSO**	9	10 1430-1700 **EODMOBUNIT3** Coronado Island	11 1230-1500 **Fleet Mammals** NRAD Point Loma	12	13
14 *GRUNIONs!*	15 ***NEW MOON*** *GRUNION HUNT*	16 **DARPA DAY** 1500-1700 **CH-46 Rotor** **ONR** Rump *GRUNION HUNT*	17 1230-1530 **Helo Squadrons** **(HC-3/HSL-41)** North Island	18 0930-1130 **EODMOBUNIT3** Coronado Island **ETO**	19	20
21	22 1400-1630 **USS Boxer/LHD4** 32nd Street Naval Station	23 1230-1500 **Fleet Mammals** NRAD Point Loma	24	25	26	27
28	29	30 **WRAP UP DAY**	31 1300-1530 **Helo Squadron** **(HC-3)** North Island			

Military Visits

(Bottom Line)

- "(We) now have a new set of priorities. Before...talked about architecture, bits, multichip modules, thruput, etc. Now...are talking about ruggedness, reliability, repairability, friendly interfaces, and a variety of operational uses. It would be difficult to overstate how important these visits are to us and in the longer term - to the Marines *(and Army, and Navy and Air Force)*."

  - Dick Urban, DARPA PM, May 1993

- Steve Wax, Where Are You?

  (You Promised Me You'd Have A Better Quote)
- WHYDFTFT?